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Installation and evaluation of LORAC precise navigation system.

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UNITED STATES
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THESIS

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ABSTRACT

A navigation system has been established on Monterey Bay using the LORAC principle of phase-comparison. It is intended primarily for use in ocean sciences research within a 25 mile radius of Moss Landing, California. The system offers the capability of repeating a previously held position within a few feet, and may be used as a general navigation aid in the area with accuracy on the order of 100 yards. The theory of operation and error-causing factors are discussed in detail. Transmitter and receiver installations are described. Chapter IV is intended to serve as a self-contained user's guide, with instructions on the operation of the receiver, suggested techniques for use, and a description of the performance to be expected. A computer program is included to provide grid charts with hyperbolic position lines plotted for any desired area or scale. Brief initial testing indicated a high degree of stability and repeatability, however further evaluation over a longer period is necessary.

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CHAPTER I

INTRODUCTION

The LORAC principle is based on the phase-comparison of two audio signals which have a common origin, but travel different paths to a common point. The phase comparison provides a set of hyperbolas, along each of which the phase between the two signals is a constant value. The family of hyperbolic lines may be laid down on a chart or map to provide geographic lines of position, or the number of lines may be counted and converted to an accurate measurement of the distance between the two antennas. If two families of hyperbolas are used, the resulting network will provide a position point where two lines of position intersect.

In particular this paper is concerned with the establishment and evaluation of a navigation system in the area of Monterey Bay. The equipment is approximately fifteen-year-old, type "A" LORAC equipment, used previously in southern California and obtained by the Postgraduate School when declared excess by its user. The objective is to provide a precise means of repeating any station previously held, with a desired degree of repeatability on the order of several feet. Its use is intended initially as an aid in ocean sciences research, and as a reference for other navigation systems under development, in the area within a

25 mile radius of Moss Landing, California. The requirement of repeatability is in contrast to a system of high accuracy where the exact geographical location is known, although such a system could be provided as discussed later. Since the system is to be used as a navigation aid, the contents of this paper will be limited to this mode of LORAC operation.

There are several publications which detail operation, computations, maintenance, trouble-shooting, and planning for the LORAC system and its equipment. They are listed in Table 1. This paper is not intended to be a substitute for these manuals, but rather a presentation of the factors considered and the details of installation for the established navigation system. These manuals should be referred to for further information.

1. THEORY OF OPERATION

Operation of the network is in the high-frequency band. Two basic frequency allocations are required, separated by at least 20 KHz, and in the range from 1.7 to 2.5 MHz. The network consists of three fixed transmitting stations, designated as the green, red, and center (or master) stations, and two fixed receivers, one each at the green and red stations. The user, with a mobile receiver at point "P" in the usable area of the network, is capable of receiving both frequencies. The center station alternates transmission between the two basic frequencies, one for use with the green station and the other with the red station.

TABLE 1

ASSOCIATED PUBLICATIONS ON LORAC THEORY AND OPERATION

Technical Manual for Radio Transmitting Set AN/TRN-2X and Radio Set AN/TRN-3X, NAVSHIPS 93068.
Includes operation, calibration, and installation instructions, schematics, and trouble-shooting procedures for the transmitters.

Technical Manual for Radio Receiving Set AN/SRN-7, NAVSHIPS 93118.
Includes operation, calibration, and installation instructions, schematics, and trouble-shooting procedures for the mobile receiver.

Computer's Manual, Seismograph Service Corporation, 1959.
Contains information essential to the performance of required mathematical procedures associated with LORAC phase measurement equipment as used in position fixing and line measurement operations.

Survey Officer's Manual, U.S. Army Engineer Research and Development Laboratories.
A guide for planning and supervising the operation of a portable LORAC System.

The green station transmits a single frequency which is an audio frequency of 135 Hz below the center green frequency, and its receiver is tuned for the mean of the two red frequencies. The red station transmits a single frequency which is 315 Hz below the center red frequency, and its receiver is tuned for the mean of the two green frequencies.

There are twelve distinct frequencies or modes of transmission applicable to the operation of the entire network, although they do not all exist at the same time. They are listed in Table 2. It should be noted that subscripts and superscripts are used rather extensively in an effort to distinguish between the many similar terms in the development to follow. They are summarized as follows:

Subscripts: g - green frequency, or part of network

r - red frequency, or part of network

m - frequency at center station

p - location of mobile receiver

Superscripts: r - modulated by n_r

g - modulated by n_g

Due to the alternate switching between f_{gm} and f_{rm} at the center station, there effectively exists two distinct cases. These will be referred to as the green cycle when f_{gm} is being transmitted, and as the red cycle when f_{rm} is transmitted. It must be realized that there are two separate conditions existing during normal operation of the network.

Consider first the green cycle (see Figure 1a). The center station is transmitting the center green frequency,

TABLE 2

LIST OF FREQUENCIES EXISTING IN THE LORAC NETWORK DURING NORMAL OPERATION

f_{gm} - center green frequency

f_{rm} - center red frequency

f_g - frequency at green station (green frequency)

f_r - frequency at red station (red frequency)

mean $f_g = (f_g + f_{gm})/2$ - mean green frequency used for tuning the receivers

mean $f_r = (f_r + f_{rm})/2$ - mean red frequency used for tuning the receivers

$n_g = f_{gm} - f_g$ - green beat frequency

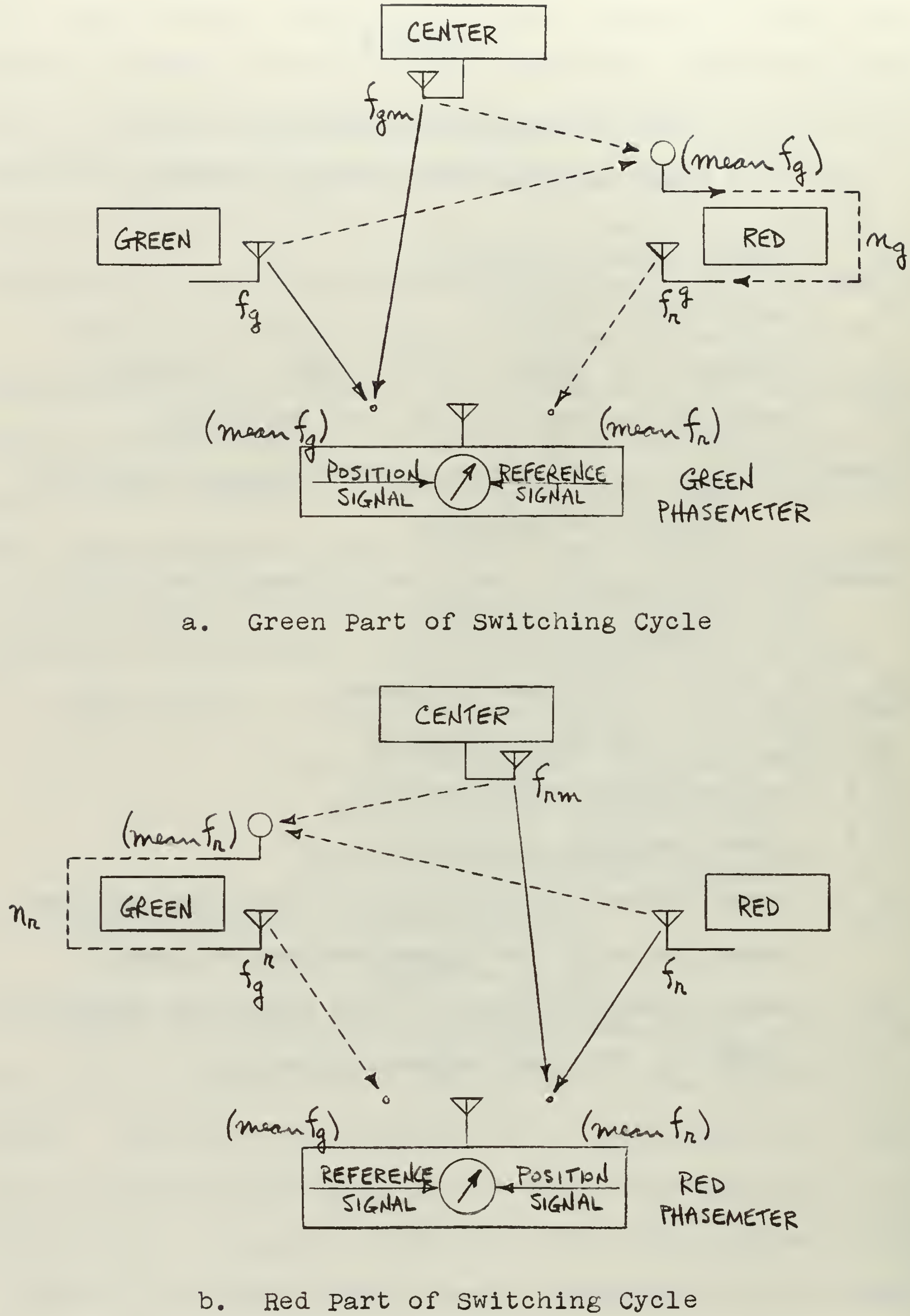
$n_r = f_{rm} - f_r$ - red beat frequency

f_r^g - red frequency modulated by n_g

f_g^r - green frequency modulated by n_r

n_g' - result after detection of the modulated red frequency at point "P" (green reference signal)

n_r' - result after detection of the modulated green frequency at "P" (red reference signal)



a. Green Part of Switching Cycle

b. Red Part of Switching Cycle

Figure 1. LORAC Switching Cycles

f_{gm}, and the green station is transmitting green frequency, f_g. These frequencies are received at point "P" and are heterodyned in the green channel to produce the green beat frequency, n_g. This is available as one input to the phase-comparison circuitry, and is called the green position signal. These two frequencies are also received at the red station. They are heterodyned in the red receiver, providing the green beat frequency for modulation of the red frequency. The signal transmitted by the red station, f_r^g, is received in the red channel of the mobile receiver and detected, providing the second input to the phase-comparison circuitry, n_g'. It is known as the green reference signal, and it may be assumed constant within the network, since it changes phase with the propagation of the audio signal. That is, for 135 Hz modulation, it suffers 360° phase change in approximately 2220 kilometers. The frequencies which form the position signal, however, change phase with the RF signal of about 2 mhz which has a 360° phase change (one wavelength) in approximately 150 meters. Movement of the mobile receiver relative to the green and center stations may therefore cause large changes in the phase of the position signal. If point "P" does not move, the distances to the green and center stations, and therefore the position signal, will remain the same. If point "P" moves in a direction such that the distances to the green and center stations are increased (or decreased) by the same amount,

the mobile receiver will not produce any change in the position signal. There are an infinite number of such points, and movement along such a path will describe one of the infinite number of hyperbolas between the green and center stations. The third possibility is where the distance to the stations does not change by equal amounts. The phase of the position signal will change, as the mobile receiver crosses the hyperbolic lines.

The red cycle operates in a similar manner (see Figure 1b), with the center station transmitting f_{rm} and the red station transmitting f_r. These two frequencies are received at position "P", and are heterodyned in the red channel to form the red position signal, n_r. The same two frequencies are received at the green station and heterodyned in the green receiver, with the resulting red beat frequency applied as modulation. The green station thus transmits f_g^r, which is received by the green channel at point "P". The detected output is the red reference signal, n_r'. Since this is equal to 315 Hz, it suffers a 360° phase change in approximately 950 kilometers, and may therefore be assumed constant within the network.

A 360° change of phase between the reference and position signals is defined as one LORAC lane. The straight line joining the center station and one of the end stations is called a baseline. A mobile receiver moving along a baseline will experience a 360° phase change, or cross one

lane, in a distance equal to one-half of the RF wave-length (approximately 75 meters). This is because the center and end stations will each provide 180° of phase change, to give a total change of 360°. Therefore at any point in the network when the total phase change between the center and end stations is 360°, the position signal will change 360° and a new lane will be indicated. This is done at the mobile receiver by a counter which adds or subtracts a digit to indicate that a new lane has been entered. A dial pointer, marked in hundredth's-of-a-lane (3.6° phase change), continuously indicates the position within the lane.

The distance between lanes on a baseline is given by the formula

$$W = \frac{V}{2f}$$

where W is the lane width on the baseline

V is the velocity of propagation

f is the frequency of the RF wave

The velocity of propagation is obviously one of the parameters which will affect the phase-comparison indication. Either the end station frequency or the center station frequency could be used in determining the lane width. However the end station frequency will be used for both baselines of the network, to agree with the development of the phase-comparison equation. Knowing the lane width, the number of lanes between the end and center stations may be found, provided the distance between the antennas is known.

The number of lanes equals the baseline length divided by the lane width.

2. THE EQUATION OF PHASE-COMPARISON INDICATION

The phase of a periodic function may be expressed as

$$\phi = 2\pi f t = \frac{2\pi f r}{V}$$

where ϕ is the phase, in radians

t is time

r is the propagation distance

During the green cycle the green and center stations generate and transmit unmodulated radio-frequency signals which may be described as

$$S_g = E_g \sin(\omega_g t + \alpha_g)$$

$$S_{gm} = E_{gm} \sin(\omega_{gm} t + \alpha_{gm})$$

where E is the signal amplitude

$\omega = 2\pi f$ - is the radian frequency

α is the initial phase angle which depends on the time origin selected

The magnitude of the signals may be assumed constant. The angle, $\omega t + \alpha$, represents the phase of the signal at the time of origin. The magnitude, sine function, and the arbitrary initial phase angle will be eliminated at the receiver at the time of the phase comparison.

In the transmission from the center and green stations to point "P", some transit time is involved. This

transit time is proportional to the distance and inversely proportional to the velocity of propagation, and may be expressed as

green station to point "P": $t_{gp} = r_g/V$

center station to point "P": $t_{mp} = \rho/V$

where ρ is the propagation distance from the center station to the point "P"

Therefore the signals at "P" are delayed in time with respect to the transmitting points. This delay may be expressed as a phase angle, as follows

$$\omega_g t_{gp} = \phi_{gp} = \omega_g r_g/V$$
$$\omega_{gm} t_{gm} = \phi_{mp} = \omega_{gm}\rho/V$$

These two signals appear in the green channel of the mobile receiver, where the difference component is selected. The selection of the difference may be shown as follows. The two signals enter at the antenna and pass thru the RF amplifiers which are tuned to the mean green frequency. Each one is mixed with the oscillator frequency, ω_o, providing all possible combinations of these frequencies due to the non-linear action of the first detector. Only two components will pass through the IF strip, however; those at approximately the IF frequency. They are the sinusoids of $(\omega_o - \omega_g)$ and $(\omega_o - \omega_{gm})$ and the nonlinear action of the second detector will again form components at all possible combinations of these frequencies. The only one of interest, and

the only one which will be output from the second detector, is the difference frequency, shown as follows

$$(\omega_0 - \omega_g) - (\omega_0 - \omega_{gm}) = \omega_{gm} - \omega_g = 2\pi n_g$$

In considering the phase change due to transit time, the difference is also selected. This may be written as

$$\phi_{gp} \pm \phi_{mp} \longrightarrow \phi_{gp} - \phi_{mp} = \frac{\omega_g r_g}{V} - \frac{\omega_{gm} \rho}{V}$$

and is called the green position signal.

The red station also receives the signals S_g and S_{gm}. The transit time from each of the transmitting stations to the red station is given by

green station to red station: $t_{gr} = r_{gr}/V$

center station to red station: $t_{mr} = r_{mr}/V$

The phase of the signals at the red station is then

$$\omega_g t_{gr} = \phi_{gr} = \omega_g r_{gr}/V$$
$$\omega_{gm} t_{mr} = \phi_{mr} = \omega_{gm} r_{mr}/V$$

The sum and difference components are produced in the red receiver, where the sum is rejected and the difference is selected. This is expressed by

$$\phi_{gr} \pm \phi_{mr} \longrightarrow \phi_{gr} - \phi_{mr} = \frac{\omega_g r_{gr}}{V} - \frac{\omega_{gm} r_{mr}}{V}$$

This difference frequency is the audio signal applied as modulation of the red frequency, and transmitted from the red station. In the process of modulation and reradiation of the difference frequency, an unknown angle may be

introduced and added to the phase angle. This will be represented by ξ_r. The signal of interest from the red station to point "P" during the green cycle is the modulation on the red frequency. The carrier itself does not enter the final results. The transit time delay from the red station to the point "P" is expressed by

red station to point "P": $t_{rp} = r_r/V$

and phase delay is given by

$$\phi_{rp} = (\omega_g - \omega_{gm}) r_r/V$$

The total phase delay encountered by ω_g and ω_{gm} during the transit time to point "P" by way of the red station is the sum of these phase terms, and the unknown angle, ξ_r. This sum is expressed as

$$(\phi_{gr} - \phi_{mr}) + \phi_{rp} + \xi_r = \left(\frac{\omega_g r_{gr}}{V} - \frac{\omega_{gm} r_{mr}}{V}\right) + \frac{(\omega_g - \omega_{gm}) r_r}{V} + \xi_r$$

The receiving and transmitting equipment is designed to insure that phase changes introduced in the circuitry, such as ξ_r, remain constant over a long period of time. The fact that the magnitude of the phase delay is not known is of no consequence, since the difference between the computed and observed values of phase will be a constant. This constant can be removed by calibrating the mobile receiver at a location where the exact computed value of phase is known. The distances from the green and center station transmitting antennas are fixed, unless one of the antennas

is physically moved. Frequencies ω_g and ω_{gm} are crystal controlled to insure a high degree of stability. The velocity of propagation of electromagnetic radiation does vary with time. Its value is dependent on the physical characteristics of the earth's atmosphere at the time of the observation. However its variation is small enough so that an average value may be used for this system with satisfactory results. Eliminating these constants reduces the expression to

$$\phi_{rp} = \frac{(\omega_g - \omega_{gm})}{V} r_r$$

This equation gives the phase of the green reference signal which is the output of the red channel of the mobile receiver.

Two signals are now available for phase comparison at point "P"; the reference signal which has travelled by way of the red station, and the position signal which arrives directly from the transmitting stations. These signals are compared to obtain the difference phase angle between them. The position signal is subtracted from the reference signal so that the lane numbers, to be plotted later, will increase as the mobile receiver travels from the center station toward the end station. Carrying out this subtraction gives

$$\Psi = (\text{REFERENCE SIGNAL}) - (\text{POSITION SIGNAL})$$

$$= \phi_{rp} - (\phi_{gp} - \phi_{mp})$$

$$= (\omega_g - \omega_{gm})r_r/V - \omega_g r_g/V + \omega_{gm}\rho/V$$

$$= (\omega_g r_r - \omega_{gm} r_r - \omega_g r_g + \omega_{gm}\rho + \omega_g\rho - \omega_g\rho)/V$$

$$= (\omega_g\rho - \omega_g r_g)/V + (\omega_{gm}\rho - \omega_{gm} r_r - \omega_g\rho + \omega_g r_r)/V$$

$$= (\rho - r_g)\omega_g/V + (\rho - r_r)(\omega_{gm} - \omega_g)/V$$

where ψ is the phase angle measured at the mobile receiver

The angle ψ is measured by the position indicator at point "P". During the green cycle, as in the case being considered, the angle ψ is ψ_g and is indicated by the green phasemeter. In the red half of the switching cycle, the phase angle ψ_r is indicated on the red phasemeter. The switching rate at the center station and the circuitry in the mobile receiver are such that it gives a continuous indication of both phase angles, even though each is received only half the time. An expression for ψ_r may be written immediately by comparing the red cycle with the green cycle. The two expressions, changed to give the phase angle in degrees, are as follows

$$\psi_g = (\rho - r_g)f_g/V + (\rho - r_r)m_g/V$$

$$\psi_r = (\rho - r_r)f_r/V + (\rho - r_g)m_r/V$$

In each of these expressions, there are three frequencies involved. They are the end station frequency, the center station frequency, and the beat frequency. The second term in the expressions contains this third frequency, and is referred to as the third frequency correction (TFC).

It can be seen that the phase angle is primarily determined by the first term, since the RF frequency is approximately 4 orders of magnitude greater than the audio frequency. For this reason the two phase angles required to assume a specific location (the hyperbolic coordinates) are calculated or plotted using only the first term of the last equation. However there are some areas of the network where the TFC must be considered for one or both of the sets of hyperbolic lines. In this event it is applied as a correction to the hyperbolic coordinates.

In summary, several factors have been assumed constant or to have negligible effect. Some of these, such as constant phase change due to circuits over a long period of time, depend on circuit design and reliability of components. Others, like the third frequency correction, are only partially applicable to a system intended for repeatability rather than accuracy, i.e., the stability of the beat frequencies. The remaining two parameters mentioned in the development of the phase-comparison equation are the velocity of propagation and the stability of the RF frequencies. Of all these there are three which are deemed important and will be considered further, with the effects of variations investigated. They are the velocity of propagation, the stability of the RF frequencies, and the stability of the audio frequencies.

CHAPTER II

EFFECT OF VARIOUS FACTORS ON THE LORAC SYSTEM

In the development of the phase-comparison equation there were several terms noted as possible sources of error. In addition to these, there are many other factors which may cause an error in using the system. They may be separated into three categories: (1) instrumental, (2) propagational, and (3) geometrical. All the factors will be listed, but only those applicable to a system designed for repeatability will be considered in detail. The chapter concludes with a discussion of the application of the phase-comparison equation to the determination of position and of the network constants involved.

1. INSTRUMENTAL ERRORS

Of primary importance is the stability of the basic frequency. Frequencies in both the transmitters and the receivers are controlled by a crystal with a rated stability of 0.001 per cent. Each crystal in the transmitters is contained in an oven designed to maintain the temperature constant at $75^{\circ}C \pm 1$ degree. An accurate measurement of the frequency drift in the installed crystals has not been made. However the variation of the center station frequencies was observed to be less than ± 0.5 cycles over short periods of time. The end stations were not as stable, with

an observed variation of approximately ± 1.0 cycles.

Variation of the RF frequencies will affect the transit time of both the position and reference signals. Including all terms, the phase-comparison equation for the green part of the network may be expressed as

$$\begin{aligned}\Psi_g &= \left[(\rho - r_g) f_g + (\rho - r_r)(f_{gm} - f_g) + (f_g r_{gr} - f_{gm} r_{mr})\right] / V \\ &= \left[f_g (r_r + r_{gr} - r_g) - f_{gm}(r_r + r_{mr} - \rho)\right] / V\end{aligned}$$

For a given location all distances in the above expression will be constant. Noting that both coefficients in parentheses will be zero or positive (each consists of the three sides of a triangle), the expression may be further simplified to

$$\Psi_g = f_g K_1 - f_{gm} K_2$$

where $0 \leq K_1 \leq 2 r_{gr} / V$

$0 \leq K_2 \leq 2 R_{mr} / V$

K_1 is maximum in the vicinity of the green station and K_2 is maximum near the center station, while both are minimum in the vicinity of the red station. It can also be noted that K_1 and K_2 may not assume maximum values simultaneously. A similar equation for the red part of the network may be written by inspection, and is given by

$$\Psi_r = f_r K_3 - f_{rm} K_4$$

where $0 \leq K_3 \leq 2r_{gr}/V$

$$0 \leq K_4 \leq 2r_{mg}/V$$

The constant K_3 may assume the same maximum value as K_1, but the regions of maximum and minimum are reversed from that of the latter. K_4 assumes its maximum value near the center station and its minimum in the vicinity of the green station.

The maximum phase-meter error due to changes in the transmitted frequencies may now be evaluated from the expression

$$\Delta\Psi = \Delta f\, K$$

where $\Delta\Psi$ is the error in lanes

Δf is the frequency change

$V \approx 3 \times 10^8$ meters per second

$r_{gr} = 41{,}500$ meters

$r_{mr} = 23{,}200$ meters

$r_{mg} = 26{,}900$ meters

The maximum errors for each part of the network are equal, and occur when the end station frequency changes (assuming the proper center station frequency). Its value is 0.000276 lanes, or 0.0276 dial divisions, for a change in frequency of ± one cycle and is negligible for all practical purposes. It is interesting to note that a frequency drift of 35 cycles is required to cause an error of one division on the

phase-meter dial, but the fact is of little significance since the resulting beat frequencies would probably not pass through the audio filters.

The end and center station frequencies are heterodyned to form an audio frequency, with a maximum error of approximately ± 1.5 cycles possible in this beat frequency. For the 135 cycle signal, this is equivalent to an error of 1.1 per cent. It would be possible to minimize this error by maintaining the end station frequency at exactly 135 cycles (or 315) below the center station frequency. This could be done by comparing the beat frequency to an existing tuning fork of the proper frequency located in the end station receiver. An operator would then vary the end station frequency to maintain the resulting lissajous pattern stable. However the system has been installed with unmanned transmitting stations, and the resulting error must be tolerated. To determine the magnitude of this error, consider the expressions for evaluating the effect of frequency changes. The maximum error due to change in the beat frequency occurs when one station varies to its lower limit while the other varies to its upper limit. The maximum error in phase occurs in the red part of the network, and is given by the expression

$$\Delta\psi_r = \Delta f_r K_3 - \Delta f_{rm} K_4$$

Using maximum values for both constants, a change of one cycle for the red station and 0.5 cycle for the center

station, the resulting error is 0.00045 lanes. But both constants may not assume their maximum values simultaneously, therefore the maximum error due to change in the beat frequency is less than 0.045 dial divisions. This also gives the maximum total error due to all changes in the RF frequencies, if the limit of variation is as noted previously.

A possible source of error is the change in the unknown phase angle ξ, which is introduced in the process of modulation and reradiation of the reference signal. The phase angle for 136 Hz might not be the same as for 135 Hz, necessitating a reference phase correction. However this is considered in the circuit design, and a constant phase angle may be assumed over a narrow band around the correct audio frequency. It might also happen that a circuit component changes its value, or a replaced component may have a different value, causing a change in the reference station phase characteristic. This is removed from consideration by calibrating the receiver dials at a fixed point (such as a marked point along a dock). Prior to each use of the system, the position indicator counter and dial must be adjusted to indicate a specific reading for both sets of lanes.

A final instrumental error to be considered is the accuracy of the phase indication. As mentioned earlier the hyperbolic coordinate is indicated by a counter which

gives the lane of the mobile receiver location, and a dial with 100 divisions to indicate the position within the lane. If the receiver and its antenna are fixed, it is possible to read the indicator to $\pm \frac{1}{2}$ of one division, or $\pm$ 0.005 lanes. The receiver is quite sensitive to movement of the antenna however, and a mobile unit on the water will experience a deviation of about $\pm$ 0.02 lanes caused by even small motion of the vessel. The error in meters will be constant over the area close to the baselines, and is equal to the radius of motion of the receiving antenna. However the width between lanes in meters increases due to divergence of the hyperbolic lines, and the inability to read the dial closer than $\pm$ 0.005 lanes will be the governing factor at points far from the baseline. Random fluctuations of the dial pointer may not permit this degree of readability. To summarize the instrumental errors, there is only one component of significance. It is the ability to read the lane indicator, and it will depend on the skill of the user, motion of the mobile receiver antenna, random disturbances, and the distance from the baseline.

2. PROPAGATIONAL ERRORS

Electromagnetic radiation travels through the atmosphere at a velocity approximately equal to the speed of light (the free-space velocity of EM waves). The actual velocity is decreased by a small percentage due to the

presence of particles such as water vapor in the region near the earth's surface. The measure of this decrease is called the index of refraction, and it depends on the air pressure, the temperature, and the water vapor content in the area under consideration. The effective velocity of propagation is given by the expression

$$V = C/n$$

where V is the effective velocity of propagation

C is the free-space velocity

n is the effective index of refraction

This is the value of V to be used in the phase-comparison equation.

The first possible source of error is the velocity in free-space. The most current value of this term is given as $2.997930 \times 10^8 \pm 300$ meters per second in several reference books. This error of ± 1 part in 10^6 will cause a similar error in the lane reading, but since it is constant over the network it is removed from consideration by calibrating the receiver prior to each use.

The index of refraction varies with the temperature, pressure, and water content of the atmosphere in the region under investigation. The dependency on the weather is usually given in terms of a modified index, N, which is related to the index of refraction by the expression (1)

$$N = (n-1)10^6 = \frac{77.6}{T}\left[p + 4810\frac{e}{T}\right]$$

where T is the air temperature in degrees absolute

p is the air pressure in millibars

e is the partial water vapor pressure in millibars

The instantaneous (exact) value may be calculated for any given time and place, if the wet and dry bulb temperatures and the air pressure are recorded. A set of tables such as the Smithsonian Meteorological Tables (2) (the table numbers given below refer to this publication) are necessary, and the procedure is as follows:

(1) Record t, t', and p

(2) Convert t and t' to $^{\circ}C$ (Table 3), and p to millibars (Table 9 or 11), if not recorded in these units

(3) Solve for $T = t + 273^{\circ}$ degrees absolute

(4) Determine the saturation vapor pressure e' from Table 94, using t' as entering argument, and the correction Δe from Table 98, entering with quantities t' and (t-t')

(5) Solve for $e = e' - \Delta e$, the partial water vapor pressure

(6) Calculate the modified index using the quantities T, p, and e.

The index of refraction and the exact velocity of propagation may now be determined.

The expression for modified index may also be used to construct a monogram giving approximate values of N

for a given air pressure. Such a monogram is shown on page 2-10 of the Computer's Manual, with entering arguments of air temperature and relative humidity, and a correction term for variations from 30.00 inches Hg. This approximation was used to determine the range of values to be expected in the Monterey Bay area. Data compiled from observations at the Monterey Peninsula Airport over a ten-year period was used for average and extreme values of temperature and relative humidity. It is realized that these values are not necessarily equal to those which might be found in the center of the network, but they should give a good approximation until better data is available. Average values for air pressure were obtained from the Marine Climatic Atlas of the World (3). The monthly and yearly averages are listed in Table 3. Using extreme temperature and relative humidity values (not shown) and the average pressure, the approximate modified index was found to vary from a minimum value of 310, to a maximum value of 420. The annual average was 323.9, using the yearly averages listed in Table 3. The relative humidity at 12 noon was used in all calculations, except that for the minimum value which corresponds to a record low temperature. The relative humidity at 0700 hours was used in this case.

The maximum deviation of the modified index from the average is on the order of 100, corresponding to a change in actual index of refraction of 1 part in 10^4. The effect of this deviation on the phase indicator may be

TABLE 3

SUMMARY OF AVERAGE WEATHER COMPILED AT MONTEREY PENINSULA AIRPORT OVER A RECENT TEN-YEAR PERIOD

Month	Temp °F	% Relative Humidity	Pressure in.Hg	Modified Index
Jan	50.1	72	30.1	320.0
Feb	52.0	69	30.1	320.0
Mar	51.8	65	30.0	317.5
Apr	53.4	74	30.0	324.0
May	55.2	72	30.0	324.5
Jun	57.7	74	29.9	328.5
Jul	58.1	76	29.9	331.0
Aug	58.6	77	29.9	332.0
Sep	59.4	74	29.9	331.0
Oct	58.7	69	30.0	326.5
Nov	54.4	66	30.1	320.0
Dec	52.2	67	30.1	319.0
Annual	55.1	71	30.0	323.9

determined from the general expression

$$\Psi = f(k_1 - k_2)/V$$
$$= nf(k_1 - k_2)/C$$

where $f \approx f_g \approx f_{gm} \approx f_r \approx f_{rm} \approx 2.3 \times 10^6$ Hz

$C \approx 3 \times 10^8$ meters per second

$0 \leq k_1 \leq 2r_{gr}$

$0 \leq k_2 \leq 2r_{mr}$ or $2r_{mg}$

The maximum magnitude of $\Delta\Psi$ will occur when k_1 is maximum and k_2 is zero, which is physically impossible due to the network configuration. However this condition will be assumed to exist in evaluating $\Delta\Psi$ from the expression

$$\Delta\Psi = \Delta n f(k_1 - k_2)/C$$
$$= \Delta n f(2r_{gr})/C$$
$$= \Delta n(635)$$

A change in the index of refraction of 1 part in 10^4 yields a maximum error of 0.0635 lanes. This is a sizable error, but two points must be considered. The first is that this maximum cannot be attained due to the network configuration, and in fact, the error is zero when $k_1 = k_2$ which occurs at the center of the network. The second point concerns the magnitude of Δ N used in obtaining the maximum value of error. It was based on an extreme condition of the weather (in this case, a very hot day with high relative humidity) which rarely occurs in this area and is even less likely

over the water. The monthly averages of weather yield ΔN's on the order of 10 or less, corresponding to a Δn of 1 part in 10^5 and a maximum $\Delta\psi$ of less than 0.6 divisions of the dial. In general the user may assume that the error introduced through changes in the refractive index is less than 1/100 of a lane, and therefore may be neglected.

The error in the phase-meter indication is actually due to changes in the velocity of propagation, rather than individual changes in the free-space velocity or index of refraction. An average velocity of propagation was computed to be 2.99696×10^8 meters per second using the average modified index of 323.9, and is used for all computation in the network. The effects of variations from this average value are those mentioned above for the refractive index. It is expected that any variations of the phase-meter indication noted by a monitor receiver and recorder will be caused primarily by changes in the velocity of propagation.

Other propagational errors concern the change in phase of the electromagnetic radiation as it travels along the earth's surface. This is the result of an interaction between the RF wave and the boundary which causes the transit time from the transmitting station to the mobile receiver to be greater than that given by the quotient of distance and velocity. The lag in phase angle is a function of (1) the refractive index at the surface, (2) the electrical properties of the surface, (3) the frequency of the radiated energy, and (4) the distance to the receiver. Consideration of the

corrections for phase is greatly simplified by assuming the earth to be flat in the usable area of the network. Terman (4) states that the effect of the earth's curvature is entirely negligible up to a distance of $50/(f_{mc})^{1/3}$ miles, where f_{mc} is the frequency in megahertz. For an RF frequency of 2.3 MHz, this distance is equal to 38 miles (about 61 kilometers). Since the area of intended use for this system is within a 40 kilometer radius of Moss Landing, the assumption of a flat earth is appropriate. Phase delay due to vertical refraction and corrections for the diffraction of radio waves around the earth's surface may now be neglected.

Several other existing conditions also simplify the problem. All three transmitting stations are located very near the water's edge, giving homogeneous propagation paths entirely over sea water. Therefore there is no need to consider mixed paths where part of the transmission is over land, with the remaining distance over water. There are no mountains or other large obstacles between the antennas and the mobile receiver to necessitate correction for diffraction around large obstacles. Finally consideration of refraction and reflection in the earth's atmosphere is not necessary because of the relatively short distances to every point in the network. One factor which must be considered is the lag in phase angle, dependent on the functions mentioned above. The procedure for computing the correction

using the plane earth theory is given in Section 3-2 of the Computer's Manual. The computations were carried out using the constants

$f = 2.3$ MHz

$V = 2.99969 \times 10^8$ meters/sec

$n = 1.0003239$

$\sigma = 4 \times 10^{-11}$ emu - sea water conductivity

$\epsilon = 81$ - sea water dielectric constant

$a = 6.37 \times 10^6$ - earth's radius

$\alpha = k = 1$ - modification constant

The results showed a maximum phase lag of 8° (2.2 dial divisions) at a distance of 40 kilometers from the transmitting antenna. The correction to be applied to the phasemeter reading is given by the relationships

green correction = (phase lag along ρ) - (phase lag along r_g)

red correction = (phase lag along ρ) - (phase lag along r_r)

which approach their maximum magnitudes near the transmitting sites. However this correction is constant for any given location and does not effect the repeatability of the system. If the parameters such as velocity of propagation and frequency do change, the resulting error is only a small percentage of the maximum correction of 2.2 dial divisions, and may therefore by considered negligible in all respects.

A final propagational factor which may introduce errors in the phasemeter reading is reradiation of the RF energy from objects near the antenna. Any metal object such as a building, power line, fence or other antenna may absorb RF energy and reradiate a portion of it. This phenomenon is used to advantage in antenna arrays by placing parasitic elements at proper locations, but it is detrimental to this system. There is no way to predict the magnitude of the error, so an effort must be made to prevent its occurance. The effect will be negligible if there is a distance of 200 meters or more to the metal objects, or if they can be broken up into very short sections. At a transmitting antenna the effect is to move the center of radiation from the antenna toward the reradiating object. This introduces a constant error at each position in the network, and will not affect the repeatability of a given location. The effect at the end station receiving antennas is to introduce a constant amount of phase change in the reference signal which can be removed by calibrating the mobile receiver. In both cases a fixed metal object was assumed. If the object is moving, or is added to or removed from the existing surroundings, the effect will be unpredictable and error will be introduced. The effect at the mobile receiving antenna may be important, since it is moving from point to point. Objects fixed from one reading to the next will not affect repeatability, but moving objects within one hundred meters,

such as another vessel close aboard, will cause errors in proportion to the magnitude and phase of the reradiated signal. Orientation of the mobile receiver with respect to incoming signals may be of some importance, if the effective receiving antenna varies with aspect angle. The effect of non-fixed parasitic radiators in the vicinity of any antenna used with the system is significant, and care must be taken to avoid them.

There are two propagational errors which must be considered in a system designed to provide repeatability. The first is caused by changes in the velocity of propagation resulting from meteorological extremes, and may be as large as 4 divisions of the phase meter dial. Under normal conditions, it will be less than 1 division and may be neglected. The second possible error is caused by metal objects near a LORAC antenna which absorb and reradiate RF energy. The error may be removed by proper calibration of the receiver, if the object is fixed during the period of system use. For a moving object, the error is unpredictable.

3. GEOMETRICAL ERRORS

There are several factors introduced by the geometry of the hyperbolic lines which affect the degree of precision. The first to be considered is the third frequency correction, which is the second term of the phase-comparison equation involving the beat frequencies. The TFC is a constant for

any given point in the network, and as such will have no effect on the capability of repeating a given station. However its characteristics will be described at this time. Examination of the terms in the TFC reveals that it generates a set of hyperbolic lines, similar to the position lines but with the two stations on the opposite baseline acting as foci. Its value is zero on the line midway between the two stations, and the magnitude of the correction increases toward either of the end stations. The maximum magnitude is easily determined by taking the baseline length times the beat frequency, divided by the velocity of propagation. The TFC is used to correct hyperbolic coordinates determined by the first term of the phase-comparison equation.

The width of the LORAC lane on the baseline is given by the equation

$$W = \frac{V}{2f}$$

and is equal to one-half the RF wavelength. Due to the hyperbolic nature of the position lines, the lanes increase in width away from the baseline. A measure of this increase is the lane expansion factor, defined as

$$F = \frac{1}{\sin \Phi}$$

where F is the expansion factor

Φ is $\frac{1}{2}$ the angle subtended at point "P" by radius vectors from "P" to the transmitting antennas.

Each point in the network has an expansion factor for both the red and green sets of position lines. The expansion factor is equal to one on the baseline, and it increases as "P" moves away from the baseline. The lane width at any point in the network is given by

$$LW_g = F_g W_g$$

$$LW_r = F_r W_r$$

Since the indicator can be read to only 1/100 of a lane, there is an unavoidable error of $\pm$ 0.005 lane always possible. In distance it is a minimum on the baseline where the lane width is minimum, and increases as the mobile receiver travels away from the baseline. At a frequency of 2.3 MHz W is equal to 65 meters, for a minimum error in position readability of 0.65 meters. At a point where F is equal to 2 for both parts of the network, the error present in reading each line of position is 1.3 meters. This does not give the accuracy of the position fix however. The lane width and the accuracy of the phase indication for the two sets of lines combine to place the observer in a parallelogram, referred to as the "diamond of error" in hyperbolic grid navigation systems. The major axis of the parallelogram is a measure of the geometric uncertainty of the position, and it attains a value of approximately 6.5 meters at a point 40 kilometers from Moss Landing. The precision with which a position may be read is therefore less than $\pm$ 3.25 meters over the intended area of use.

Within the triangular area formed by the three stations, the maximum geometric uncertainty is less than $\pm$ 1.1 meters, provided dial readability is the limiting factor.

4. LORAC NETWORK CONSTANTS

In order to relate the hyperbolic coordinates given by the phasemeters to an approximate geographical position it is necessary to determine the dimensions of the LORAC network. These dimensions are referred to as the network constants, and they are based on a rectangular grid system to simplify computations. This is in contrast to a geographical grid which would require computations in a spherical coordinate system. Since the area to be considered is relatively small, the difference in results is negligible. In the rectangular system all East-West and North-South coordinates are straight lines and intersect at right angles. The Universal Transverse Mercator (UTM) Projection was selected for use since UTM grid coordinates are given on topographic maps published by the U.S. Geological Survey. This projection is based on distances in meters, with 1000-meter intervals indicated on the maps. The UTM coordinates of a given location may be obtained from 7.5 minute series topographic maps, accurate to about $\pm$ 10 meters.

The coordinates of the transmitting antennas were obtained by the method just described. Since the location of the various antennas on the map had to be estimated, the

accuracy of their coordinates vary. The UTM coordinates of the green and center stations are considered accurate to ±20 meters since recognizable objects nearby were shown on the maps, while the location of the red antenna is only good to ±100 meters. This lack of knowledge of the transmitting antenna coordinates is the primary reason the established system can not provide an accurate position fix, in addition to repeatability. The accuracy of a geographical position fix can be no better than the uncertainty in its reference, which is the antenna position in this case. Besides the coordinates of the antennas, the operating frequencies of the network and the velocity of propagation must be known. A computer program (see Appendix A) has been prepared to compute the remainder of the network constants, and present them in a form similar to that shown in Figure 5-6 of the Computer's Manual. The constants for the installed system are given in Table 4, where

E,N	are the UTM coordinates of the stations
f_g, f_r	are the end station frequencies
n_g, n_r	are the beat frequencies
f_{gm}, f_{rm}	are the center station frequencies
V	is the velocity of propagation
h,k	are the coordinates of the baseline center
d	is the baseline length in meters
c	is one-half the baseline length
α	is the positive angle from the E-W coordinate axis of the center station to baseline

TABLE 4

LORAC NETWORK CONSTANTS

E_m	608220.000	N_m	4073100.000
E_g	587625.000	N_g	4090395.000
E_r	600820.000	N_r	4051110.000
f_g	2355865.000	f_r	2275685.000
n_g	315.000	n_r	135.000
f_{gm}	2356000.000	f_{rm}	2276000.000
V	299705985.300		

	Green	Red
h	597922.50000000	604520.00000000
k	4081747.50000000	4062105.00000000
E	-20595.00000000	-7400.00000000
N	17295.00000000	-21990.00000000
d^2	723271049.99999990	538320099.99999990
d	26893.69907618	23201.72622888
c^2	180817762.49999970	134580024.99999970
c	13446.84953809	11600.86311444
cos α	-0.76579276	-0.31894179
sin α	0.64308744	-0.94777431
W	63.60848039	65.84962007
L_T	422.80052773	352.34411685
L_{min}	788.59973614	1823.82794157
ϵ	1000.00000000	2000.00000000
L_{max}	1211.40026386	2176.17205843

W is the lane width on the baseline

L_T is the total number of lanes between stations

L_{min} is the lane number at the center station

$\mathcal{L}$ is the arbitrarily chosen number of the center lane

L_{max} is the lane number at the end station

If more accurate information on the antenna location becomes available or the operating frequencies are changed, it is only necessary to change the data cards and a new set of network constants will be computed.

5. PREPARATION OF HYPERBOLIC GRID CHARTS

While not absolutely necessary, it is convenient to have a chart showing the hyperbolic lines of position, related in some way to the geographical features of the area. The hyperbolic grid lines are plotted using only the first term of the phase-comparison equation, that is

$$\psi_g = (\rho - r_g) f_g / V$$
$$\psi_n = (\rho - r_n) f_n / V$$

The plotting procedure may be summarized as follows. The lane midway between the stations is assigned an arbitrary number from which all other lane numbers are determined, and is then plotted. To plot every 5th LORAC lane, for example, a distance equal to 5 lane widths is taken along the baseline from the baseline center. This point is used to calculate the coordinates of other points on the fixed

lane number equal to the center lane number ± 5 lanes, from the two formulas

$$E = h + a \cos\alpha \cosh\mu - b \sin\alpha \sinh\mu$$

$$N = k + a \sin\alpha \cosh\mu + b \cos\alpha \sinh\mu$$

where a is the distance in meters from the baseline center to the desired lane at its point of intersection with the baseline

$b = \sqrt{c^2 - a^2}$

c is one-half the baseline length

μ is the hyperbolic argument selected arbitrarily

The quantity, a, is positive if going toward the end station and negative if toward the center station. The sine and cosine terms are positive or negative depending on the orientation of the baseline. Therefore the signs in the last expressions have all possible variations, and the equations yield four sets of E, N coordinates of points placed symmetrically about the baseline and its center. This divides the area to be plotted into four quadrants, with quadrant 1 in the far left corner when looking from the center station, and the remaining quadrants numbered 2 through 4 in a counterclockwise direction of rotation from quadrant 1. The hyperbolic angle μ is a variable and is used to determine the density of points calculated on each hyperbolic line, as well as the maximum distance to be plotted from the baseline. Having determined a sufficient number of points, the

points are plotted and the two hyperbolic lines are drawn. The distance from the baseline center is then increased by intervals of 5 lanes, with points plotted for each lane, until the end stations are reached. Further details are provided in Section 5-5 of the Computer's Manual.

The computer program shown in Appendix A is a general program in that it will plot the hyperbolic grid lines for any LORAC system, if certain network constants and the desired chart characteristics are provided on data cards. The program is liberally described by the use of comment cards, but will be discussed briefly. Double precision is used throughout. The first part of the program computes the network constants necessary for preparing the hyperbolic grid charts. The first seven lines of the printed output (see Table 4) list the contents of the first group of data cards, which are the most recent information on the transmitting antenna coordinates, the operating frequencies of the system, and the velocity of propagation. The specification of the desired chart are read, followed by three point plots. They are (1) a 3-point plot (squares) of the station locations, (2) a 30-point plot (x's) of the Monterey Bay shoreline, and (3) an 18-point plot (plus signs) of various navigation aids and landmarks to provide a link between the prepared grid charts and the existing nautical charts for the area. The position of the points plotted in (2) and (3) above is only an approximation. They have been transposed from a nautical chart to the rectangular grid by describing

the desired points and the station location in terms of yards referred to a common point (the intersection of a latitude and longitude line). Two reference points were used, one each in the vicinity of the green and red stations.

The remainder of the program calculates the points to be plotted. The order of calculations starts with the left outermost point (quadrant 2) on the hyperbolic line nearest the center station, proceeds toward and passes through the baseline, and thence toward the right outermost point (quadrant 3) of the lane. Only those points which lie within the desired chart area are retained, and are plotted prior to moving to the next lane. After the center lane is plotted (a straight line) the calculations proceed from quadrant 1 to quadrant 4. Lanes described by three or less computed points are disregarded. The lane number of each plotted line is listed in the printed output, and it is necessary to label the lines by hand from this list. Extreme care must be taken to label the lanes in the proper order, and to match the graph output with the printed list of lanes when more than one graph is plotted at one time. The output chart is 9 x 15 inches, and any number of grid charts may be produced in one program by inserting additional data cards in the proper location. The arguments necessary to obtain a desired plot are listed in Table 5. Prior to the end of a plot, the three station locations are plotted again (shown as plus signs) to check for errors in positioning of the plotter between the start and finish of the plot.

TABLE 5

DESCRIPTION OF ARGUMENTS FOR

OBTAINING DESIRED GRID CHART

Columns	
1-12	XMIN - the western boundary of the desired area in UTM coordinates
13-24	XMAX - the eastern boundary of the area; the value of (XMAX-XMIN)/9 determines the scale of the grid, and it is highly desirable to choose a convenient scale; example - XMAX = 615000.0, XMIN = 570000.0 yields a chart scale of 45000/9 = 5000 meters per inch
25-36	YMIN - the southern boundary of the area
37-48	YMAX - the northern boundary of the area; the value of (YMAX-YMIN)/15 must equal (XMAX-XMIN)/9
49-60	DELLAN - gives the interval in lanes between plotted lanes; example - DELLAN = 5.0 plots every 5th lane
61-72	DELMU - determines the density of points calculated and plotted; a satisfactory relation between the chart scale, DELLAN, and DELMU is given by

Scale	10K	5K	3K	1K	500	200 meters/in
DELLAN	25.0	10.0	10.0	5.0	2.0	2.0 lanes
DELMU	0.10	0.10	0.10	0.05	0.02	0.02

73-80	PMUMAX (optional) - determines the outer limit of plotted lines; it is set to 2.0 which is satisfactory for most areas, if the option is not used

The required order of data cards is as follows: (1) the necessary network constants - 7 cards, (2), the position of the red and green stations in yards to a reference point on the nautical chart - 2 cards, (3) the position of arbitrarily selected points along the coastline - 30 cards, (4) the position of various navigation aids, landmarks, etc. - 18 cards, and (5) a specification of the parameters for the desired plot (any number of cards, one plot per card). Grid charts of two different scales have been prepared, and are available in a 9 x 15 inch size. The first covers the entire bay, with a scale of 3000 meters per inch, and is shown in Figure 2. The second available scale is 1000 meters per inch and consists of a set of 15 charts which cover the same area. An example of these is shown in Figure 3 for the vicinity of Point Pinos.

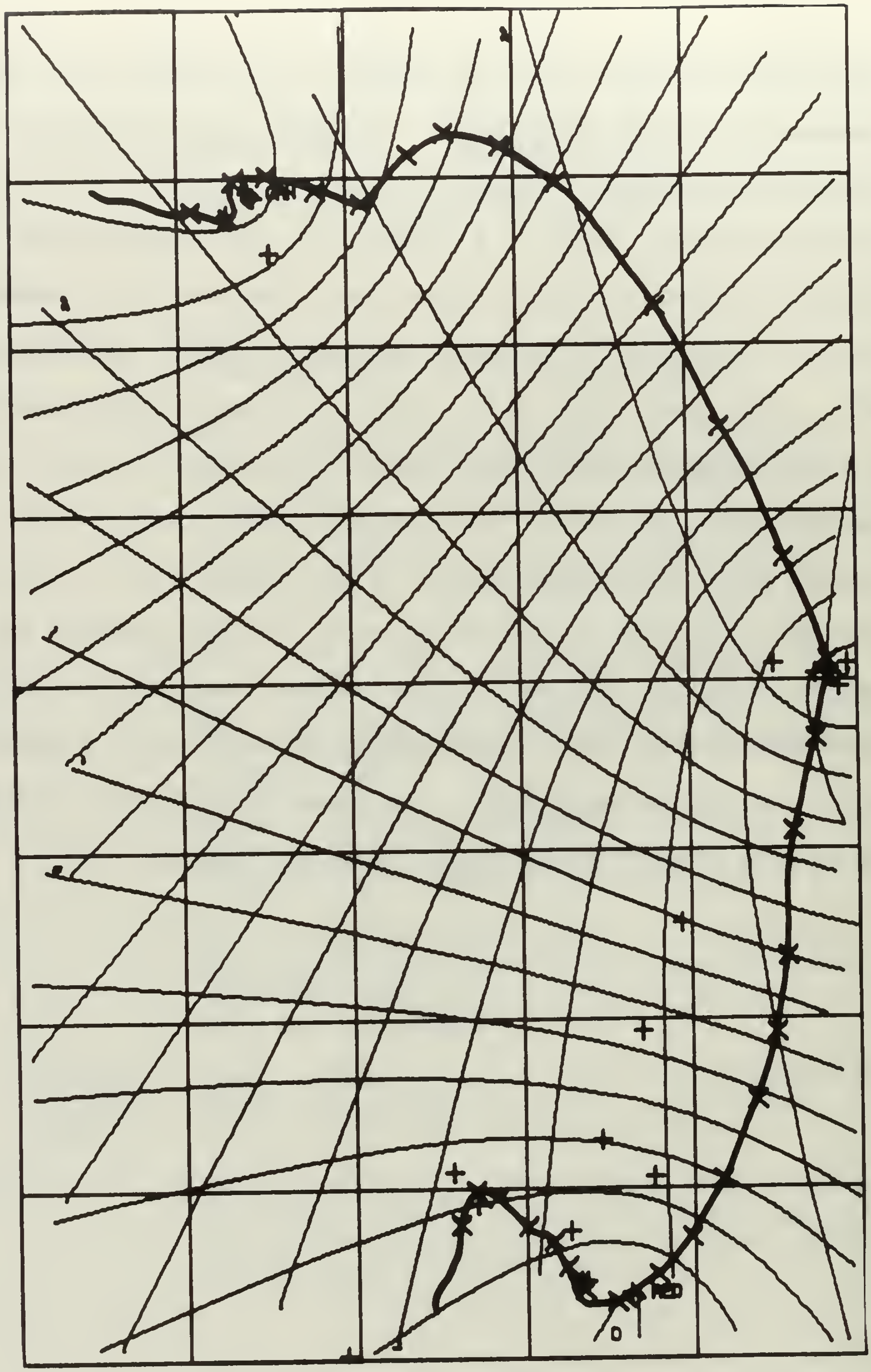


Figure 2. Prepared Chart of Monterey Bay, Scale 1 inch = 3000 meters.

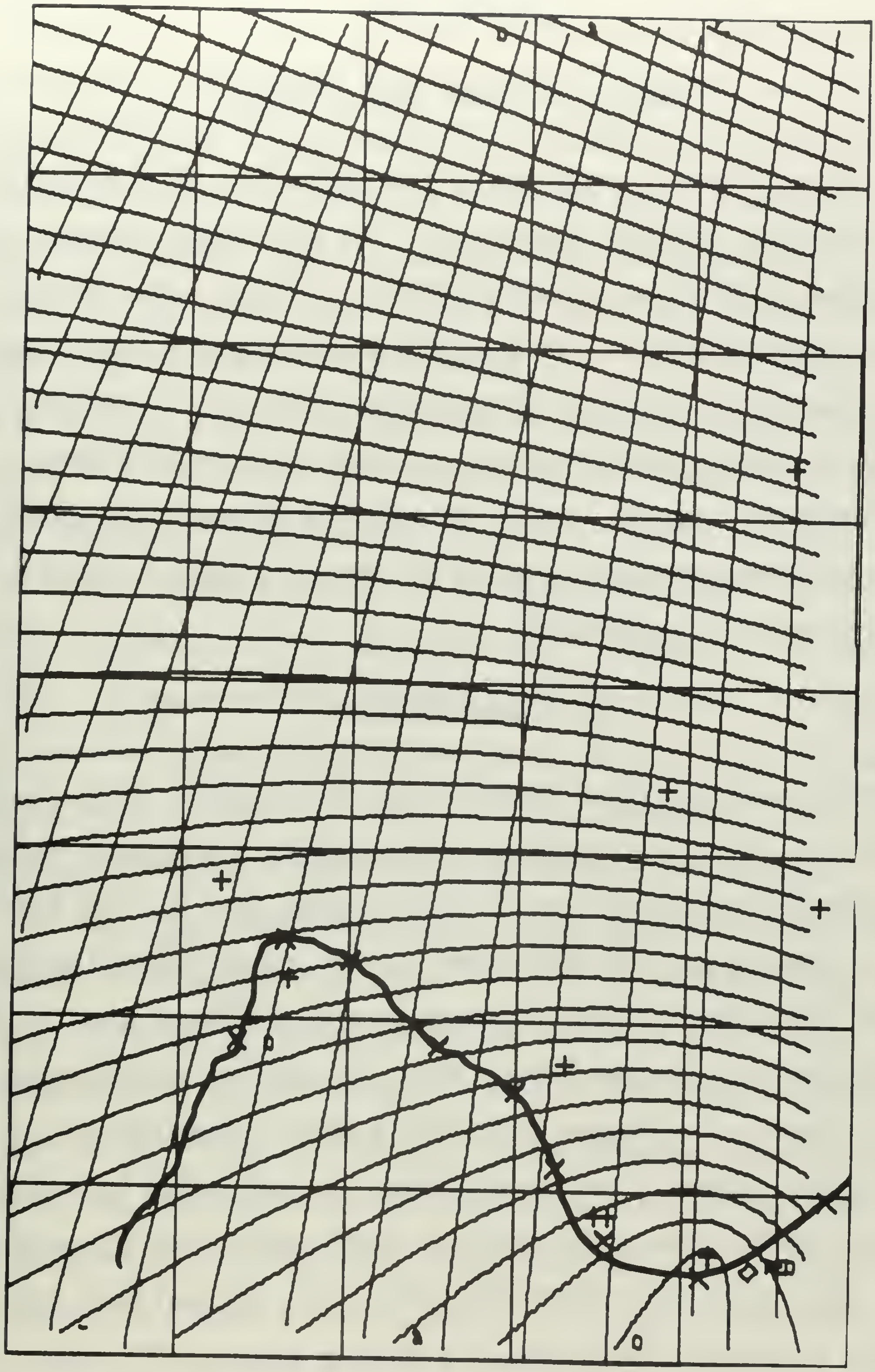


Figure 3. Prepared Grid Chart, Scale
1 inch = 1000 meters.

CHAPTER III

LORAC EQUIPMENT AND STATIONS

The equipment required in the operation of a complete LORAC (type-A) network consists of (1) one Radio Transmitting Set AN/TRN-2X for the center station, (2) two Radio Transmitting Sets AN/TRN-3X for the red and green stations, and (3) at least one receiver with phase-measuring equipment, such as the Radio Receiving Set AN/SRN-7 for mobile use. Since complete details on the standard equipment are given in the technical manuals listed in Table 1, only a brief description will be offered.

1. TRANSMITTERS

The center station transmitter is designed for continuous wave type AO emission, alternately switching between two crystal-controlled frequencies in the band 1.7 to 2.5 MHz. A power input of 500 watts to the final amplifier will provide 300 watts of output power across a 52-ohm load. The set operates on 115 vac $\pm10\%$, 50 to 60 cycles, single-phase line voltage and consumes 1100 watts when operating at rated output power. The transmitter is contained in three separate units, the power supply, oscillator, and RF amplifier. Each unit is 15"x22"x28" deep, and is designed for stacking on top of each other to form a package 45" high weighing approximately 380 pounds. The units are inter-

connected by a cable harness. A block diagram of the set is shown in Figure 4. Line power is supplied to the transmitter through a connector on the front of the power supply which provides 1750 and 400 volts dc for the RF amplifier and 115 volts ac for all units. The three switches on the front of the power supply are the only ones which require handling after the initial adjustment of the station. They are (1) "AC Power", which permits heater voltage for all tubes and for the crystal oven, and is always left on except for equipment maintenance, (2) "L.V." (low voltage), which applies 400 volts dc to the RF amplifier, and (3) "H.V." (high voltage), which applies high voltage to the RF amplifier. A relay delays the application of high voltage for 15 seconds after the L.V. switch is turned on. A second relay cuts off the ac power to the transmitter if a high voltage overload occurs for more than a few seconds.

The oscillator contains two crystals for each frequency, a normal and a spare, with each contained in an oven. The oscillator circuit is a Pierce oscillator, and frequency may be adjusted for each of the four crystals by dials on the face of the unit. Frequencies are switched by a free running multivibrator which alternately removes the negative bias on both the buffer and output amplifier stages by grounding their grids. The switching rate is adjustable, and should be set at about five switches per second. It has been observed that too low a rate does not

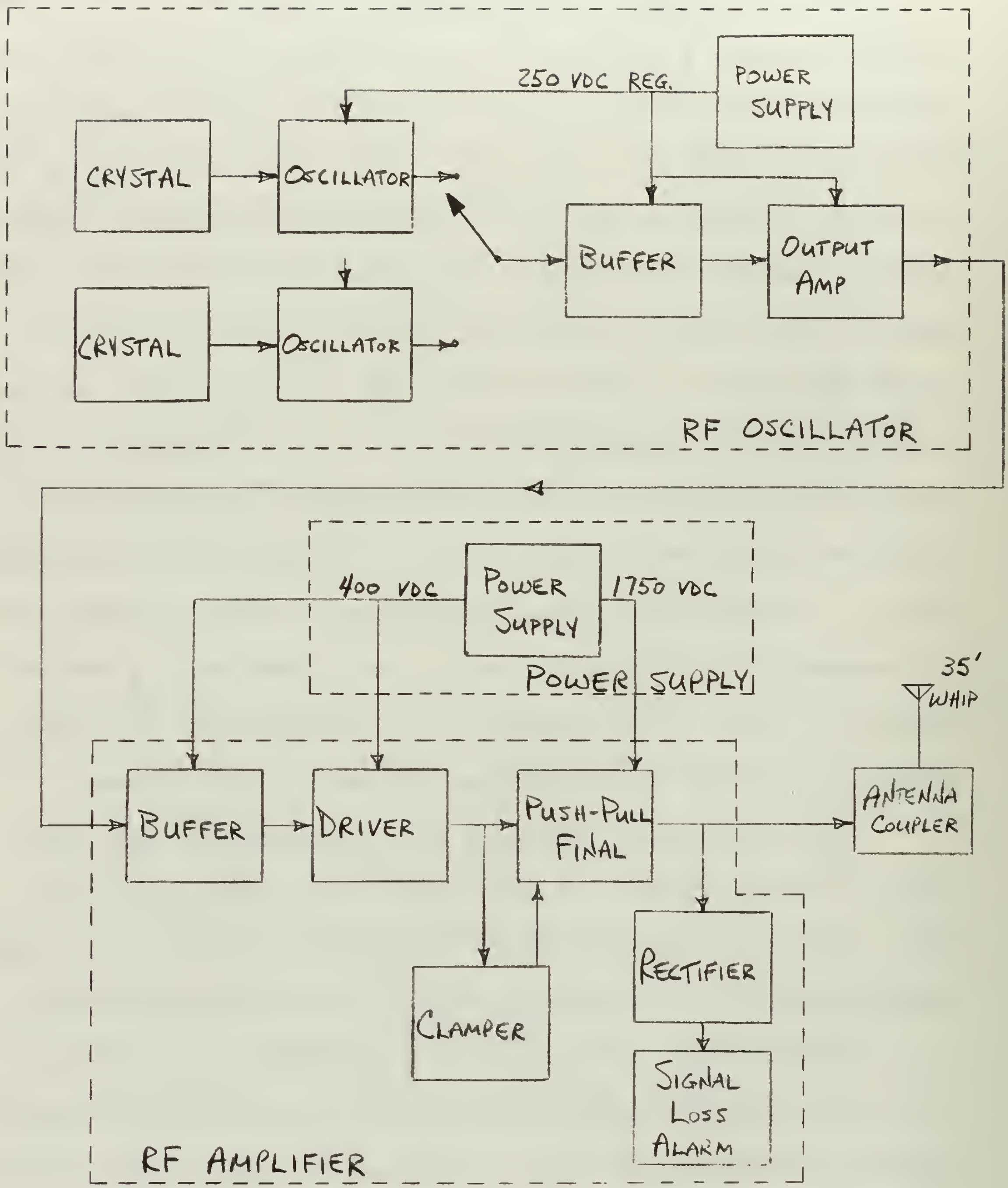


Figure 4. Block Diagram of Center Station Transmitter.

permit the grids to return to the cutoff condition immediately. This allows both frequencies to be transmitted for a portion of the time, which should be avoided. A 5-position switch (function selector) selects either (not both) of the frequencies as a continuous or switched on-off signal, or both frequencies alternating (normal operation). The oscillator contains a regulated power supply which provides 250 volts dc to the plates of all tubes in the unit.

The RF amplifier consists of buffer and driver amplifiers, and a push-pull final amplifier. In the center station the 1750 volts is applied directly to the plates of the final stage. A portion of the RF output signal is fed to a rectifier, which in turn decreases the plate current to about 150 milliamperes (versus 360 ma in normal operation). The final tubes are thus protected in the event of driving voltage loss. A 3-position switch on the front of the RF amplifier offers selection of tuning, alarm off, and normal modes. In the tuning position the grid of the clamper tube is grounded, thus protecting the final tubes if the output circuit is not properly tuned. RF output power is provided to a connector on the front of the RF amplifier.

The adjustment procedures are given in the technical manual. They are straightforward, and involve the setting of proper dc voltage levels. For tuning the transmitter, there are five controls and three meters on the front of the RF amplifier. The controls are (1) final grid tune, (2) final grid drive, (3) final plate tune, (4) antenna tune, and (5)

antenna coupling, and the meters are (1) final grid current, (2) final cathode current, and (3) antenna current. A dummy load is provided for checking the overall operation of the transmitter. A 300 watt input at the dummy load results when the antenna current is equal to 2.5 amps, with final grid at 25 ma and the final cathode at 360 ma. The plates of the final tubes will have a slight orange glow. A bright orange color indicates some misadjustment or malfunction, and the set should be returned to the tune position immediately. In tuning the center station, it is necessary to alternate the function selector between the two positions which provide continuous signals, until the same meter reading is obtained for both frequencies. The tuning procedure in the technical manual is satisfactory for use with the dummy load.

The reference data for the end station transmitters is similar to that given for the center station, with two exceptions. The emission alternates between continuous-wave type A0 and amplitude-modulation type A9, at the rate of switching at the center station, and consumes 2000 watts. The end station transmitter consists of five units, the power supply, the modulator, the RF amplifier, the oscillator-oscilloscope, and the receiver. The total package is 75 inches high and weighs approximately 700 pounds. The first four units listed are interconnected by a cable harness, while the receiver is connected by separate cable to the modulator. This permits mounting the receiver in the

vicinity of the loop antenna provided with the equipment. A block diagram of the green station transmitter is shown in Figure 5, with the frequencies present at various points given. The power supply and RF amplifier units are identical to those found in the center station, and may be interchanged. Concerning the RF amplifier however, tuning is much easier since there is only one frequency at either end station. An output of 300 watts into the dummy load serves as an overall performance check on the transmitter, as before. A modification has been made to the RF amplifier at both end stations. A sample of the RF output is provided to the oscilloscope by a voltage divider consisting of resistors R1310 and R1311. This signal is used with a sample of the modulator output to provide a trapezoid on the scope for determining percent modulation. To obtain a satisfactory height of the pattern, the resistor R1310 was changed from 3.3K to approximately 2.5K ohms of higher wattage rating (replacement value differs between sets).

The oscillator provides a single frequency, and the circuitry is identical to that of either channel in the center station oscillator. The regulated power supply provides 250 volts dc to the modulator driver tubes, in addition to the tubes within the oscillator. The receiver is of the superheterodyne type, with a crystal controlled local oscillator operating at a frequency 455 KHz above the RF frequency. At the green station this is the mean red

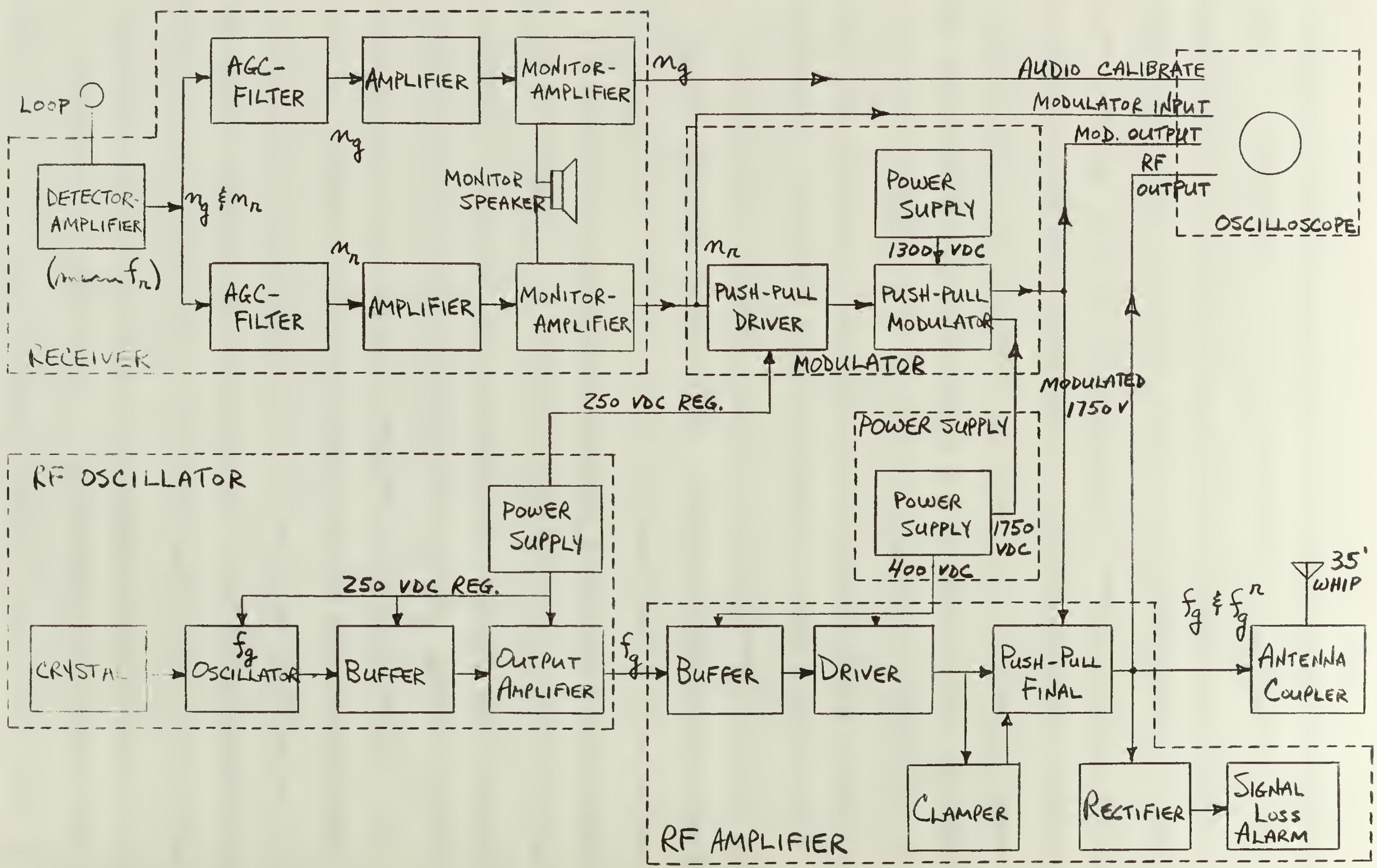


Figure 5. Block Diagram of Green Station Transmitter.

frequency. The signal is received by means of a three-foot diameter, shielded loop antenna. An AVC voltage is applied to both RF stages, the converter, and both IF stages. The receiver is designed for a sensitivity of five microvolts and a 6db bandwidth of 3 KHz. In normal operation of the network, the red frequency is being received continuously, but modulated with the green beat frequency half of the time. The receiver is also receiving the center red frequency during the other half of the time. Therefore there are two audio signals alternately available at the output of the second detector, i.e., the green beat frequency and the red beat frequency. Immediately following the detector-amplifier there are filters at 135 and 315 cycles. These serve to route the audio signals to the proper channels. An AGC circuit controls the amplitude so that the modulator receives constant amplitude signals. The monitor-amplifier circuit provides a signal to a speaker for aural monitoring of the system, and contains a switch which routes the proper signals to the scope and modulator, depending on the set's use as the red or green station. At the green station, the green beat frequency is routed to the oscilloscope where it may be compared with the frequency derived from a tuning fork. The resulting lissajous pattern is then observed while the RF frequency is adjusted. A stationary pattern indicates that the transmitter is at the proper frequency below the center green frequency. The red

beat frequency is to be transmitted as modulation on the green frequency, and is routed to the modulator.

Contrary to the center station, the high voltage (1750 volts dc) from the power supply is sent to the modulator. The modulating signal from the receiver is applied through a T-pad attenuator which adjusts the amplitude and controls the percent modulation. This signal is also applied to the oscilloscope for monitoring purposes. The audio signal is amplified in the driver and modulator stages, where it appears in the secondary of the output transformer in series with the 1750 volts dc. This modulated high voltage is then routed to the RF final amplifier where it provides plate modulation of the RF signal. The oscilloscope receives several signals for monitoring operation. They are the audio calibrate signal (n_g), the modulator input (n_r) and output, the RF output, the tuning fork output, and any desired signal through a "Y input" connection. By use of two function switches, many useful presentations may be observed, including the lissajous for calibrating frequency, a trapezoid for determining percent modulation, modulator input compared to output for detecting modulator troubles, and the RF output for overall performance. Adjustment and tuning procedures are listed in the technical manual.

Since both types of transmitters were designed for use with 100-foot towers, the antenna couplers provided with the equipment were unsuitable for the 35-foot, collapsible whips

used. Satisfactory antenna couplers had to be fabricated to match 52-ohm coaxial cable to an antenna impedance of approximately 3 ohms resistance with a high capacitive reactance. Several excess antenna couplers were available, and using the components in them, the circuit shown in Figure 6 was used in all couplers. This circuit is not considered to be the best for the situation, but it did permit standing wave ratios at the antenna base of less than 1.3 to 1 at the end stations, and at the center station when only one frequency was transmitted. The whip antenna is bolted directly on top of the box containing the antenna coupler. The coupler is tuned by movable taps on the coils,

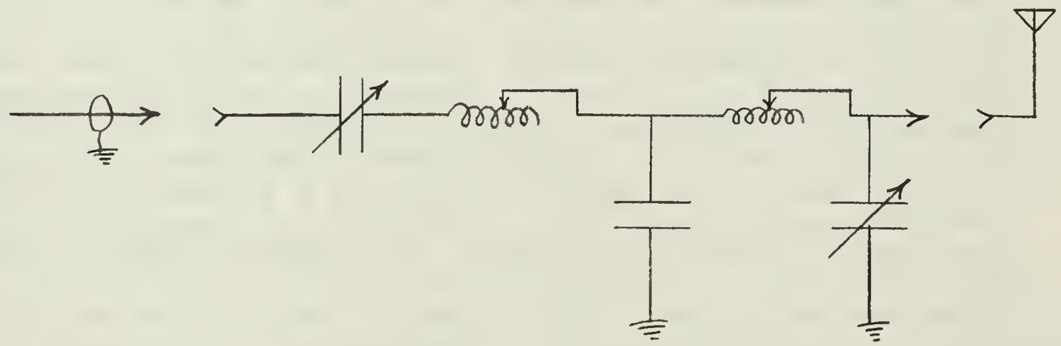


Figure 6. Antenna coupler circuit

and by screwdriver adjustments through the front of the box for the two air-gap capacitors. An ammeter is located on the front of the coupler box to give an indication of the antenna current. SWR indicators provided with the LORAC equipment may be used.

The various stations are located at Santa Cruz, Moss Landing, and Monterey. The red station (Monterey) was installed on property along the beach belonging to the Naval Postgraduate School. The transmitter was placed inside Building #2 at the Beach Antenna Lab, where power and protection from the weather were available. The transmitting antenna and coupler are mounted approximately 15 feet above ground level, on a platform attached to a telephone pole. The pole is part of a rhombic antenna system, however it is not presently being used and there are no wires attached to it or any of the others in the field. The area is clear of metal objects which might cause interference for a distance of at least 400 feet, and the antenna is approximately 300 feet from the waterline of the bay. The loop antenna is mounted on a heavy tripod which came with the equipment, and is located about 250 feet from the transmitting antenna. The line between the two antennas is such that it is perpendicular to a second line drawn from the transmitting antenna to a point midway between the other two stations. This permits the loop to be oriented for a null on the nearby antenna, while receiving a maximum signal from the green and center stations. The connections from the transmitter to the two antennas were made using buried coaxial cables intended for the rhombic antenna. Both connections consist of short leads from the transmitter to a patch panel which connects Building #2 with Building #1, and thence to terminal boxes near the antennas. Short leads

were required from the boxes to the antennas. At all stations RG-8A/U coaxial cable (52 ohm) was used if available. Of the three station sites, Monterey most nearly approximates the ideal station layout.

The green station is located on the end of the municipal wharf in Santa Cruz, through the cooperation of the City Parks and Recreation Department. The transmitter is installed in a small storeroom in a city-owned building at the very end of the wharf. It was necessary to mount it on a platform 24 inches above the floor in order to clear water pipes. This fact may make trouble-shooting difficult. Power is supplied through a 20-amp circuit breaker in the master panel located nearby (no other services on the breaker), and the set is grounded to a water pipe in the storeroom. Additional receptacles were installed for test equipment. Keys to the storeroom and the master panel have been obtained, so that 24-hour access to the equipment is possible. The transmitting antenna is bolted to the coupler box and is set on the roof immediately above the transmitter. A piece of plywood was placed beneath the coupler to prevent damage to the roof. The antenna is guyed at its mid-point with three wires equally spaced. Aircraft cable was used for the guys, with an insulator near the antenna in each one. Coaxial cable was run from the transmitter, through the back wall, and over the edge of the roof to the coupler, for a total length of 25 feet. The loop antenna is mounted on the top of a

14-foot length of 2-inch pipe, to discourage persons from tampering with it. It was originally set at the edge of the dock and strapped to the existing fence, at a point approximately 80 feet from the transmitting antenna, with the connecting cable run overhead. It is planned to add an 8-foot section of 3-inch pipe to the bottom, bolting the entire pole to the dock, and leading the cable beneath the dock to the storeroom. There are many objects in the vicinity of the antennas which might cause interference, including 40-foot metal light poles. The site is far from ideal, and was selected solely for the availability of the location.

The center station has been installed at the Marine Laboratories in Moss Landing, through the cooperation of Dr. John Harville. The transmitter is located in the furnace room on the ground level, and sits on a small platform to preclude any possible problems with water on the floor. Power is supplied through a 20-amp circuit breaker to a receptacle box, with no other services on the breaker. The antenna and coupler were mounted on a small platform, designed to fit securely on the crest of the roof without the need for placing holes into or through the roof. The position of the antenna was selected arbitrarily, with the idea in mind that it might have to be moved at a later time. It is guyed at its mid-point with three lengths of aircraft wire, equally spaced around the antenna. Insulators are inserted near the antenna end. The coaxial cable is run from the transmitter to the attic alongside the air duct,

then across the attic and out through the wall beneath the overhang of the roof, and to the coupler. The antenna is approximately 300 feet from the water's edge, and as such, the transmitted signal must pass over land for a mile or more on the direct path to Monterey. However this condition does not apply to a mobile receiver in the area of expected use. Other adverse conditions include a 20-foot metal pole about 100 feet away on the same roof and large metal buildings 300 feet away. In initial tuning of the transmitter, problems were encountered with RF potentials on the chassis. Suspecting an inadequate ground, two 6-foot iron rods were driven alongside the building and connected directly to a ground lug on the transmitter. Further investigation revealed that the problem was due to a mismatch for the green frequency. The tuning procedure was revised to favor this frequency for high power levels, and no problems occured when power was reduced.

2. RECEIVERS

The AN/SRN-7 is the standard receiving set for mobile use with the LORAC system. It is effectively a combination of the two receivers found at the end stations. Refer to Figure 7. Each detector-amplifier is a superheterodyne, crystal controlled channel as in one or the other of the end stations, and each has both of the audio frequencies available at the output of the second detector. The check switch relay is provided to give a reference reading on the

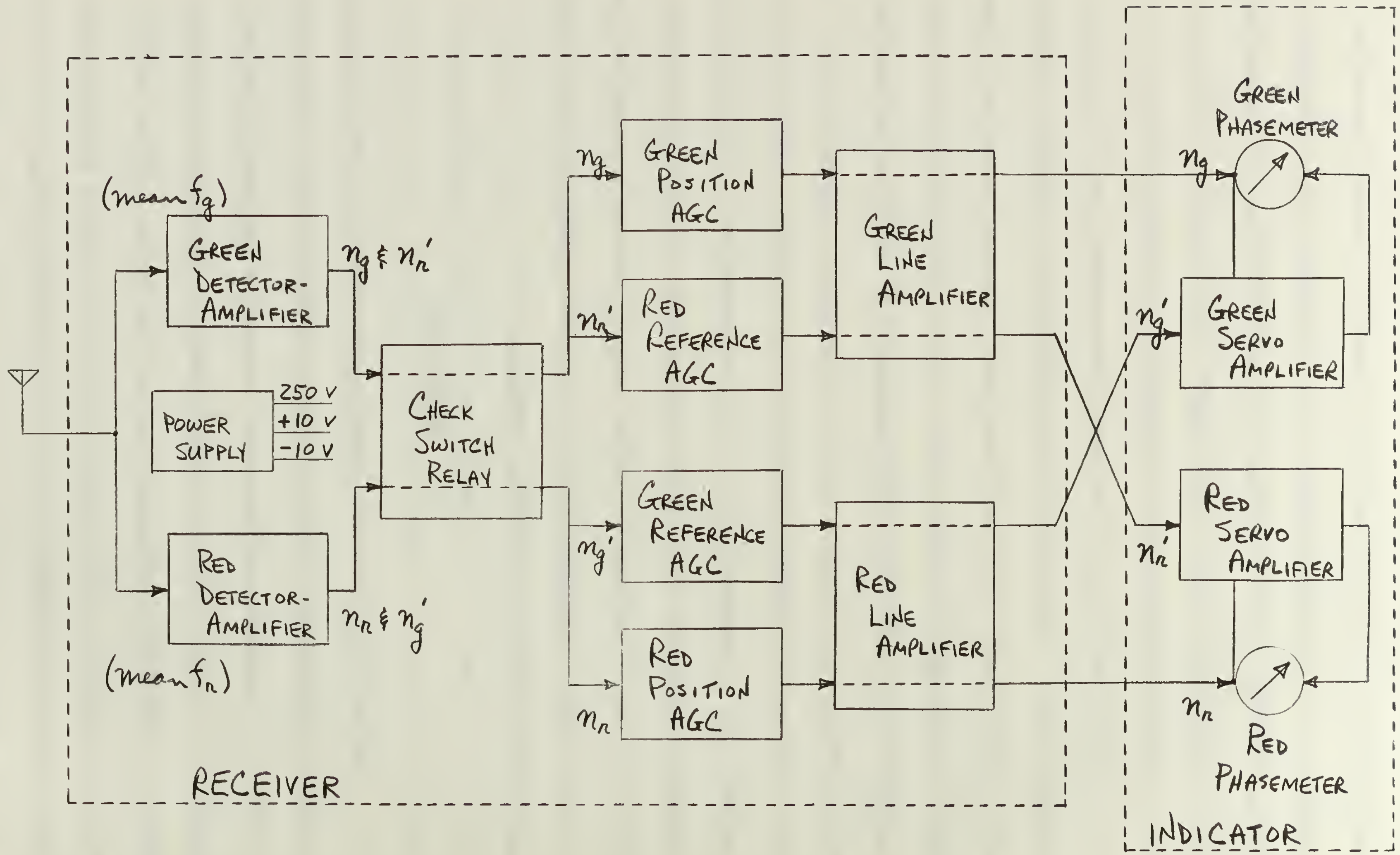


Figure 7. Block Diagram of LORAC Receiver-Indicator.

phasemeters, which serves as a quick check for proper equipment operation. This reading is recorded after the receiver has been calibrated in the network, and will always be the same if the equipment is operating properly. This is done by tying all four AGC circuits together and with a single input signal. Only one position of the phase meter can be assumed, unless the relative shaft position between a resolver and its servo drive motor is changed. The AGC and filter circuits reject unwanted and pass correct frequencies, and control the amplitude of the output signals so that the line amplifier receives constant amplitude signals. The positive and negative 10 volts dc from the power supply are used as a reference for the AGC action. A Signal Fail Alarm circuit in the reference AGC's causes a warning light on the indicator to come on when the reference signal is lost. The position AGC has two filters in its circuit, while the reference AGC only has one. This is to balance the number of filters which each signal passes through. The reference signal passes through a filter in the receiver of the end station prior to being received at the mobile unit. The line amplifier is used to match the high impedance of the AGC circuits to the relatively low impedances of the phase-comparison circuitry. The indicator contains a servo amplifier, resolver, servo drive motor, and selsyn transmitter for each part of the network. Considering the green phase meter, the action may be briefly described as follows. The green position signal

from the green line amplifier is applied directly to the resolver. The servo amplifier receives two signals, the green reference signal from the red line amplifier and the signal from the resolver. If an unbalanced condition exists between the two, there is an unbalanced voltage fed to the servo drive motor. The motor rotates until the resolver, which is connected to the motor shaft, has been repositioned such that the servo amplifier sees a balanced condition. The indicator dial pointer follows the rotation of the motor shaft, tripping a counter each time the zero position is passed. A selsyn transmitter is also attached to the motor shaft, and is available for use to drive auxiliary equipment, such as a strip recorder.

There are three operating receivers, while a fourth is available but inoperative. There is one navigational recorder available which records lane changes by a counter and lane position to 1/100 of a lane. The most important receiver installation will be that of a system monitor. The receiver and indicator should be kept in a place where the various switches will not be accidently bumped. A recorder should be used to record short and long term variations in the system. The antenna should be fixed, and isolated from other antennas or objects which might be moved. Another important installation is that on the Naval Postgraduate School research boat. Plans have been drawn up for a permanent installation, to be installed in the near future. The receiver will be mounted beneath an

existing table, as will part of the indicator. The face plate of the indicator and everything attached to it will be removed and rebuilt into a small, custom-built cabinet which is to be placed in the limited area directly in front of the boat's controls. The necessary cables will connect the two sections. The starboard whip antenna will be used to receive LORAC signals, since it is not in use. The LORAN antenna coupler presently installed at the base of the antenna may be by-passed, if necessary, when the installation is made. The required 115 volts ac is available on the vessel. Several temporary installations have been made. One was on the CGC LAMAR, stationed in Monterey, for a two-day period. A fixed, inverted-V antenna, designed for receiving LORAN-A, was used with good results. A second installation at the Coast Guard Station, Monterey, used a 12-foot whip without a coupler successfully over a two-week period. A temporary monitor station set up in the lab used a length of wire hanging from a window. No coupler was used, and there were several large buildings between it and the network, yet the receiver stayed locked on for the period of the test.

3. THE TOTAL SYSTEM

The complete system was placed in operation on 18 November 1968. Parts of the network were operated at earlier times in the process of experimenting with antenna couplers, tuning and adjustment of transmitters, etc. The basic

operating frequencies of the network are 2276 and 2356 KHz. These two frequencies have been authorized for use by the Commandant, 12th Naval District, on a temporary noninterference basis terminating 1 February 1969. The frequencies are assigned to the stations as follows:

center green frequency	- 2356.000 KHz
center red frequency	- 2276.000 KHz
green frequency	- 2355.865 KHz
red frequency	- 2275.685 KHz

When the network was initially turned on, each of the transmitters were operating near the designed output power of 300 watts. Transmitted power from the antennas was on the order of 100 watts. An effort has since been made to reduce the transmitted power to the minimum level necessary to cover the area of intended use. The system has been established with unmanned stations, causing some difficulties in evaluating and calibrating the system. For this reason it has been left operating continuously. At least one individual at the sites in Santa Cruz and Moss Landing has been briefed on the operation of the transmitters, and is capable of turning them on and off and changing the mode of operation. This has on occasion inconvenienced the individual, especially in Santa Cruz where he is located some distance from the equipment.

The network has been calibrated once, using a procedure which requires only brief assistance from someone at Moss Landing. While not ideal, it does permit the minimum number of personnel (two) to check each station and calibrate the

network while doing so. The team of two starts in Monterey, performing any necessary maintenance or checks to insure proper operation. Upon departure, the red station is left on. Proceeding to Moss Landing, the station is checked for proper operation and the function selector of the oscillator is switched so that center green frequency is transmitted continuously before departing. In Santa Cruz station operation is checked and the green frequency is adjusted by means of the lissajous figure. The green station is left on, and the team returns to Moss Landing where the function selector is switched for continuous transmission of the center red frequency. At this time it is necessary to make arrangements for someone to return the set to the normal operating position at some specified time later. In Monterey the red frequency is adjusted, and when the center station is returned to normal, the network is ready for use. An alternate to this is to use a frequency counter to check each oscillator in both the normal and spare crystal positions. BNC connectors have been installed on the front of each oscillator for this purpose. Correct operation of the network may be determined by using any receiver tunable to the operating frequencies. This is indicated by the presence of both audio signals at each of the RF frequencies. Proper operation is also indicated at an end station by the observation of a properly modulated RF output signal and a reasonably stationary lissajous pattern.

There are several possibilities worthy of mention which may cause unexplainable shifts in the network lanes. One is that of a large vessel moored along the wharf in Santa Cruz. The wharf is capable of handling such a ship, but the likelihood of such an occurrence is not known. Another concerns the possibility of vandalism, especially to the loop antennas at the end stations. City employees of Santa Cruz have expressed this on several occasions, citing examples of mischief along the wharf. Even though on Navy property, the loop at Monterey presents a curious sight and is readily accessible to passersby on the beach.

CHAPTER IV

USER'S GUIDE TO LORAC ON MONTEREY BAY

The purpose of this chapter is to provide a basic understanding of how the LORAC navigation system works and the details of how it may be used. Further discussion on the theory of operation, error-causing factors, and the equipment are found elsewhere in this paper or in the publications referred to in Chapter I.

1. INTRODUCTION TO LORAC

The navigation system which has been established on Monterey Bay uses the LORAC principle of phase-comparison. Radio signals transmitted from two stations are combined to form two different signals at the same audio frequency. One signal is received directly from the two stations and is called the position signal, while the other is received by a third station and reradiated. It is called the reference signal, and its phase upon arrival at a mobile receiver is considered constant over the entire area of use. The phase of the position signal however is a function of the distances to the two stations. Lines of constant phase (constant difference in distance) form a family of hyperbolic lines with the two stations as foci. By comparing it to the reference signal, the arrival phase of the position signal is determined and the mobile receiver is then known to be

on one of the hyperbolic lines. That is, one hyperbolic line of position has been determined. By using the third station and sharing a center station, a second family of hyperbolic lines is provided. The intersection of two hyperbolic lines of position, one from each family, provides the hyperbolic position of the mobile receiver.

The hyperbolic lines of position are referred to as lanes, where one lane corresponds to a 360° change of phase in the position signal. The two stations at Santa Cruz and Moss Landing combine to form a "green" set of lanes, and the stations at Monterey and Moss Landing form a "red" set of lanes, with the center station shared by alternating its transmitted frequency between two values. The three stations form the LORAC network. Reading the green and red phasemeters at the same time provides a set of hyperbolic coordinates. Each phasemeter consists of a counter which shows the lane number, and a dial pointer, which shows the position within the lane. The counter is increased (or decreased) by one each time the pointer passes zero on the dial, which is divided into 100 divisions. This permits reading the lane number to two decimal places. An example of a reading is as follows: say the counter on the red phasemeter reads 2167 and the pointer indicates the value 90; then the mobile receiver is located on the red lane 2167.90, giving one line of position. A second line of position is obtained by reading the green phasemeter. For example, green lane 864.75 is

given by a counter reading of 0864 with the pointer directed at 75 on the green phasemeter.

The manner in which the position information is used will vary with the application and user. If it is desired to assume a particular hyperbolic position one or more times and to remain at that position for a short period of time, then the coxswain must be able to see the phasemeter dials, while maneuvering the boat as necessary to maintain the specified readings. An alternate technique would be to drift or proceed while performing the mission, noting the phasemeter readings only when some desired event occurs. The exact position of the events could then be reproduced at any convenient time. Regardless of the manner of use, it is absolutely necessary to calibrate the phasemeters at a known position prior to each use. A calibration point for the Postgraduate School research vessel has been established for its normal mooring location. Prior to each use of the system these exact readings must be set into the phasemeters. Upon return to the mooring location (within one foot), the same readings should be observed. If not, then all readings made during the trip must be considered in error, unless the user can pinpoint the time the error was introduced.

A calibration point is determined by locating the position as precisely as possible on one of the prepared grid charts. The hyperbolic coordinates (to two decimal places) of the position are then established as the calibration

values. Additional check points may be set up by the user, using such locations as the end of a dock, buoys with a small radius of swing, etc. One disadvantage of the system is that a momentary station failure will probably result in a loss of lane count, unless the mobile receiver is stopped in the water. Such a situation is indicated by warning lights on the face of the equipment or erratic and unexpected motion of the dial pointer. If this happens, the user must return to a calibration or check point to determine the correct lane count. The pointer will automatically assume the correct position when normal operation is resumed. Pre-established check points in the area of operation may save a lengthy return trip to the calibration point.

2. OPERATING INSTRUCTIONS

The receiver required for use of the LORAC navigation system is designated the Radio Receiving Set AN/SRN-7. It consists of (1) receiver, of dimensions 11"hx21"wx26"d and weight 95 pounds, (2) position indicator, of dimensions 8"hx21"wx15"d and weight 45 pounds, (3) interconnecting cable, semi-permanently attached and approximately 8 feet in length, and (4) antenna coupler, of dimensions 5"x8"x7"d and weight 4 pounds. The user should provide (1) antenna, of height 5 to 50 feet, (2) short length of 52-ohm coaxial cable to connect antenna and antenna coupler, (3) length of 52-ohm coaxial cable to connect antenna coupler and receiver, (4) a power source capable of supplying 115 vac ± 10%,

single phase, 60 cycles ± 5%, 340 watts of power (3 amperes), and (5) a suitable location for installation of the equipment. Each item is discussed further below.

The receiver unit contains circuitry to amplify and detect the necessary radio frequencies from both parts of the network, and to route the resulting audio signals through the correct path to the phasemeters. There is only one control on the front panel of the receiver, the ON-REMOTE switch. This switch is usually left in the REMOTE position, which allows both the receiver and indicator to be turned on or off at the indicator. There are also two blown fuse indicators which glow whenever the fuse is blown. It is not necessary for the receiver to be accessible to the operator. Therefore it may be placed anywhere, so long as the length of interconnecting cable will permit the indicator to be placed in a desirable location.

The position indicator contains the two phasemeters which give the position of the mobile receiver within the LORAC network. The indicator should be placed in a location where the operator can continually observe the phasemeter readings and operate the controls. This is especially important if a coxswain is required to maintain the vessel in a desired position by keeping the dials at a specified value. The controls of interest to the operator are located on the front panel of the indicator. The POWER ON-OFF switch applies power to the equipment, if the switch on the receiver is in the REMOTE position. A PHONES jack is provided so

that the signals from the network may be monitored aurally. Any high impedance headset may be plugged into the jack to listen to the signals. The MONITOR GREEN-OFF-RED control adjusts the volume of the signals heard in the headset. The green signals are heard when the control is in the counter-clockwise position, and the red signals when in the clock-wise position. Both are off when the control is centered. The PANEL LAMPS control varies the intensity of lamps in the phasemeters from OFF to full ON. The OPERATE-CHECK switch provides a check to determine that the equipment is operating properly. When the switch is depressed, the phasemeters will rotate to a predetermined position listed above the switch. The INDICATOR OPERATE-READ causes the phasemeter pointers and counters to stop when the switch is depressed to the READ position. This facilitates reading of the lane numbers to the designed accuracy. The RESET PLUS-MINUS switches will cause the phasemeter pointers to rotate rapidly in a positive or negative direction. It is used to set the proper lane count into the appropriate phasemeter, if lanes should be lost or gained due to any reason. FAIL lamps indicate the presence of insufficient signal levels to properly operate the phasemeters. The CALIBRATION KNOBS are the only controls of interest to the operator which are not located on the front panel. They are found on the inside of the front panel, and may be reached by loosening five thumb-screws on the top of the indicator and lifting the lid.

The calibration knobs are used to adjust the appropriate dial pointer to the proper value.

The interconnecting cable is connected between the receiver and indicator on all receiving sets, and no adjustments or connections are required of the user. The receiving set, with the position indicator, interconnecting cable, and power cord placed on top of the receiver, weighs approximately 150 pounds and may be easily handled by two men.

The antenna coupler is used to match the electrical impedance of the antenna to the receiver so that losses in the cable are kept to a minimum. However the relatively small area of Monterey Bay and the transmitted power from the network stations combine to produce a strong enough signal so that the coupler is usually not required. Therefore the user should try a direct connection from the antenna to the back of the receiver unit. If a satisfactory result is not obtained by this procedure, the assistance of a technician should be requested.

For the reasons just given, an antenna of almost any length will provide a strong enough signal for proper operation of the receiver. However it must be secure and not allowed to swing about. If the antenna is removed between uses of the receiver, it should be replaced in exactly the same position each time or errors will result. It is important that all metal objects in the vicinity of the antenna be in the same relative position at each use, and that the antenna be away from objects such as booms and davits which

are normally moved at the same time as the receiver is used.

Coaxial cable of type RG-58/U or RG-8/U is satisfactory both lengths, however the short length will usually not be required. All connector receptables on the receiver and the antenna coupler are of the type UG-680/U, and require connector plugs of type UG-21D/U on the cable. An appropriate adaptor may be used. The power cord is approximately 12 feet in length and is terminated in a grounded, 3-prong plug. The receiver and indicator must be located in an area protected from the weather and from abuse and rough handling. Each must be secured to prevent damage from motion of the vessel or vehicle.

The sequence of operation for the different phases of use is as follows.

(1) Starting the equipment:

(a) At least 30 minutes prior to departure from the dock, turn POWER ON-OFF switch to the ON position (if the set does not come on, check that the receiver switch is in the REMOTE position, and that the fuse lamps are out). If one of the pointers rotates rapidly, turn set off immediately and then turn on again more slowly.

(b) Adjust PANEL LAMPS, if necessary.

(c) Insert headset in the PHONES jack and listen for "beeping" sound when MONITOR control is turned to either extreme position.

(d) Turn the OPERATE-CHECK switch to the CHECK position, holding it there for about 15 seconds. Observe the pointer indication and check that they agree with the values listed on the front of the indicator.

(e) Using the RESET PLUS-MINUS switches, set the proper lane count into the counters. Note that the calibration values listed on the front of the indicator only apply to the usual mooring location.

(f) Just prior to departure, check the pointer indications to ensure that they agree with the calibration values. If not, turn the CALIBRATION KNOBS until the correct value is indicated.

(2) Operating the equipment: After leaving the dock, care must be observed to prevent bumping the ON-OFF and RESET switches. The FAIL lamps and the phasemeters should be observed closely to detect loss of signals. If a temporary loss occurs, no lanes will be lost if the vessel does not move more than one-half lane (30 meters or more). The INDICATOR OPERATE-READ switch may be used to facilitate making a reading, but it must not be held down so long that one-half lane passes.

(3) Securing the equipment:

(a) Immediately upon return to the calibration point, the reading on the phasemeter should be checked. If both the counter and pointer indicate the calibration values, then all field data may be considered correct.

(b) Turn the OPERATE-CHECK switch to the CHECK position, and check for agreement with the listed values.

(c) Secure the set by turning the POWER ON-OFF switch to the OFF position.

If at any time the correct results can not be obtained, the technician at the Postgraduate School should be notified.

3. USE OF CHARTS

A set of charts, showing hyperbolic lines of position has been prepared for the area of Monterey Bay. They are limited in size to 9x15 inches, since they were produced by an electronic computer. A master chart shows the entire area

of the bay on a scale of 1 inch to 3000 meters (1:118,110). This area is divided into fifteen grids, with a chart of scale 1 inch to 1000 meters (1:39,370) provided for each grid. Charts of this scale will be satisfactory for most purposes.

All charts are prepared on a rectangular grid where all east-west and north-south lines intersect at right angles, whereas nautical charts are shown in a geographic grid where the coordinates (lattitude and longitude) are perpendicular only at the equator. In particular the coordinate system used is the Universal Transverse Mercator (UTM) Projection, which uses the meter as the basic unit of distance. These coordinates are given in the margins of the prepared charts, and correspond directly to the UTM coordinates shown on the topographic maps published by the U.S. Geological Survey. The exact relationship between the two grid systems is complex. However to provide a means of relating the hyperbolic position lines to the geographical surroundings, the approximate location of the coastline has been plotted (shown as a series of x's) on the grid charts. The approximate location of navigational aids have also been plotted (shown as plus signs). Using these points as references, it is possible to go from the nautical chart to the hyperbolic grid chart and back, with an accuracy of about ±100 yards. It must be noted that the prepared charts use a scale in meters per inch, and that 1 meter = 1.093 yards.

If the prepared charts do not provide a sufficiently large scale for a particular application, a chart of any desired area and scale can be produced by the computer. The procedure for obtaining charts is given in Section II-5. The method of using any of the prepared charts is left up to the user. However a typical use might be as follows. A bottom sample is desired once a week for ten weeks, at a position 5000 yards due north of Point Pinos Light. It is important that each sample be taken from the same location. The user first plots the position on the appropriate grid chart (scale 1 inch = 1000 meters) by laying off a distance of 5/1.093 inches north of the plotted location for the light. The green and red lane numbers of the plotted position are read as precisely as possible (two decimal places). As each sample is taken over the ten weeks, the coxswain maneuvers the vessel so that the green and red phasemeter indicate these lane numbers during the time the sample is being taken. This procedure will ensure that each sample is taken within a few feet of the others, and within 100 yards of the desired position.

4. PERFORMANCE TO BE EXPECTED

In general the user should expect the system to allow him to repeat a previously held position within a few feet, but there are several factors which will adversely affect this ability. The first depends on the location of the user

in the LORAC network. Under the best conditions the position of the dial pointer can only be read with a precision of about ± 0.005 lanes, and when underway in a moving boat, this easily becomes ±0.01 lanes or more. If the boat is on a line connecting the center and end stations, called a baseline, the width of one lane is equal to about 65 meters. A precision of ±0.01 lanes in reading the dial is thus equivalent to ±0.65 meters. As the boat moves away from the baseline, the lane width increases due to the diverging nature of the hyperbolic lines. At a distance of 40 kilometers from Moss Landing, the uncertainty in a position fix is ±6.5 meters just due to the inability to read the dial closer than ±0.01 lanes. Therefore the user can expect much better results in repeating a station near the baselines than at the outer limits of the Bay.

The second important factor which may introduce errors is the change of the velocity of the radio signal. This depends on the refractive index of the atmosphere near the water surface, which in turn depends on the air temperature, pressure, and relative humidity. The difference in the phasemeter reading for a given location may reach 0.06 lanes if the opposite extremes of weather are experienced. However the possibility of this variation exceeding 0.01 lanes is low and the error may be considered negligible. If precise readings are required, the user may want to take this factor into account. The procedure is outlined in Section II-3.

The effect of antenna location has already been mentioned. Depending on the type of vessel used, a difference in readings might be experienced for various headings or orientations. It must be realized that the hyperbolic coordinates are for the location of the receiving antenna, and not the bow or stern of the vessel. For this reason the positions determined by one user may not be directly usable by another vessel, even though the same calibration point is used.

The stability of the system will be monitored at a fixed installation, especially during use by a mobile unit. If the time of use extends over several days, without checks at calibration points, it will be necessary to check the monitor for variations during the period. Adjustments could then be applied to the field data. In conclusion the full advantage to the user will only come with the experience of many and varied uses.

CHAPTER V

RESULTS AND RECOMMENDATIONS

Early efforts in this project were directed toward bench testing and "in lab" simulation of complete network operation. The first phase lasted several months, due to the overall poor condition of the equipment. Circuit components had to be rewired correctly in several instances, especially in the receivers. While operating with 300 watts into the dummy load, the transmitters failed several times for various reasons. However the three transmitters were finally made to operate simultaneously. The proper inputs to the receivers were provided by taking several loose turns around the RF output connector of the proper transmitter, then run to the receiver through shielded cable. In this manner the total system was properly operated for an extended period of time. The receivers were set up in the same room, with a short length of wire for an antenna. Movement of the "antenna" through distances up to 20 feet resulted in changes of phasemeter indication, while allowing it to remain stationary for a period of time resulted in constant readings over the same period. This was the extent of work done in the lab, and it proved to be of tremendous value to the author in understanding the operation of the equipment, learning proper techniques of trouble-shooting, and placing the equipment in good running condition.

1. RESULTS OF FIXED AND MOBILE TESTS

As of the time of writing, the transmitting equipment has operated continuously and correctly for a period of two weeks. During this time, only brief tests of the system have been made. The most impressive was made during an underway trip on the CGC LAMAR, within twenty-four hours of the time the network was placed in operation. Prior to departure the approximate hyperbolic coordinates of the mooring position were taken from prepared grid charts. These values were set in the indicator. While still tied to the dock, a variation of ± 1 or 2 divisions on the phasemeter resulted from movement of the ship against the mooring lines. At the time of departure (0800, 19 November), the exact readings of the phasemeters were recorded. The vessel proceeded north from Monterey harbor, and spent most of the day in the area off Fort Ord, at distances up to 15 kilometers off the beach. Several times during this period, the ship's position was determined by LORAC and compared to radar fixes taken at the same time. In each instance they agree to within 300 meters of each other, and according to the electronics technician onboard, there was reason to believe that the radar was in error by this amount. The procedure of reading the phasemeters and laying down a fix on the prepared grid charts took only a few seconds for each position. Upon return to the harbor (1530 the same day), the author was able to give correct approximate distances

to the mooring location, and to make a final statement that the vessel was moored in the same location as that morning, by observing only the phasemeters. The readings agreed exactly (less than one-half of one division) with those recorded at the time of departure. It is this high degree of accuracy in repeating a given position which is the purpose of the LORAC system on Monterey Bay.

A second mobile test was made on the LAMAR on the following day (the author did not make the trip). The meter readings were recorded at the time of departure and the time of return. During the underway period of more than 24 hours, the vessel operated in the area from Point Sur to within 300 meters of the transmitting antenna at Santa Cruz. The signals remained strong through the entire trip, however this was during the period when the transmitters were operating at a high output power level. They have since been reduced by a considerable amount, and the existance of sufficient signal level in the vicinity of Point Sur to remain locked on has not been investigated. During the trip a running plot of ship's position was kept on the prepared grid charts, and it checked closely with radar and visual fixes. This demonstrated the use of the system as a general navigation aid over the area of the bay, in addition to the repeatability feature. When the departure and return readings were compared, there were small differences noted. Converting the differentials to distances at that part of the network, it was calculated that the mobile receiver was

approximately five meters down the dock from where it had started, which was in fact about where the ship had tied up. Thus there have been two successful demonstrations of repeatability.

A second method of testing has been to establish receivers at fixed locations, and to note the variation in readings. One such receiver installed for a 10-day period at the CG Station indicated a final reading within one division of that initially set into the set. Several intermediate checks gave the same readings. The readings of another receiver, set up in the lab, were recorded from one to three times daily during a 10-day period. The resulting readings varied from the initial values less than ± one division for the green phasemeter reading, while the red reading varied from minus one division to plus three divisions. The variations generally agreed with those found on a third receiver. The third receiver was set up in the laboratory, with a navigational recorder connected to provide a continuous record of the phasemeter readings. However due to several breakdowns of the recorder, the data was discontinuous and limited primarily to the red phasemeter. During the period of 22-29 November, the red channel was recorded for a period of 128 hours, and the green channel for 64 hours. The results of these recordings were studied, but they are not presented due to several questions concerning their validity. However the several observations made

by the author are presented in the following paragraphs.

In all three receivers it was noticed that the red phasemeter was much more erratic than the green phasemeter. Random variations of up to five divisions were noticed on the red dial, but variations on the green dial were limited to one-half of one division. The recorder did not follow these variations. It was also noticed that the red meter would experience periods of rapid chattering, lasting up to a minute, but these were recorded. It seems unlikely that all three receivers should simultaneously experience a malfunction causing this erratic action, so the idea of proximity to the red station was considered. The input signals to the red phasemeter were reduced to a level much less than those to the green meter, yet the random variations of the dial continued until the level was too low to drive the servo. The RF level into the red channel was reduced by detuning the RF transformers with no success. The opportunity has not occurred to observe the meters with the receiver in the vicinity of the green station, which should shed some light on the matter. In any event this phenomenon which occurs only for the red station should be understood, or at least accounted for, before a thorough analysis of stability can be made.

The variations just discussed refer to those of very short duration, on the order of seconds. Drift of the phasemeter over longer periods of time was observed on the recordings, and these are the measure of system stability.

The majority of the drifts noticed were long term, occuring over a period of an hour or more. This is the effect which may be expected from the gradual change in the velocity of propagation caused by weather changes. Of particular interest was the period of 0200-1000 hours (all times are local times). In five out of eight possibilities the phasemeter reading was observed to decrease by 1 to $1\frac{1}{2}$ divisions, starting between 0200 and 0600, and ending between 0800 and 1000. The readings then increased by a similar amount at various times through the day. Several distinct short term changes were noted, over periods lasting from one to thirty minutes. Three in particular were noted, lasting one or two minutes each and resulting in changes of one-half to more than one division of the phasemeter dial. A final observation was the presence of a period of increased activity in the variations during the period of 1800-2200 on several evenings. These were not the rapid variations mentioned first, but a series of short term drifts. No explanation can be offered for these.

Several important items will now be mentioned in conclusion of the results. One measure of the use of this system is the effect on the observed positions if the stations are turned off for a period of time. On one occasion the center station was turned off for 20 minutes. During this time all receivers maintained the proper lane count and returned to the correct dial reading when the

transmitter was turned on. The effect with all stations turned off for a longer period of time remains to be investigated. During the underway testing of receivers, a maximum speed of about 12 knots was attained. When the ship's course crossed lanes perpendicularly, the phasemeter was indicating a new lane every 15 seconds. The servo of the indicator will track the signal at a faster rate than this, but there is a limit which should be kept in mind. With the dial pointer rotating at the speed given, it proved easier to read the slower moving dial as the faster pointer indicated zero, than to risk losing a lane by using the OPERATE-READ switch to stop both pointers.

2. RECOMMENDATIONS

Of primary importance is the need for the continued and thorough evaluation of the installed network. While initial tests are indicative of a satisfactory navigation system, there are many areas requiring further work which could be the subject of another thesis. One is the establishment of a system monitor station, or possibly two. The best site would probably be in the center of the network, but since this is physically impossible, locations such as Point Pinos or the Soldiers' Club of Fort Ord might be satisfactory. However a monitor located at the Postgraduate School, which is near to the baseline extension of the red part of the network, would offer an ideal position to study the effects of red frequency variations and the

changes in the velocity of propagation, as well as convenience. Others include the design of a remote controlled, on-off device so that the system need not be left on continuously, the design of an overlay system to determine lane count if lanes are lost for any reason, and the study of phase-pattern distortions in the vicinity of the Moss Landing and Santa Cruz stations, and other areas of interest. The maintenance requirements for the system are unknown at this time, however plans should be made to set up a spare parts kit to affect on-the-spot repair of minor problems. It is assumed that a technician from the Postgraduate School will maintain the equipment, at least for the immediate future.

The results of further evaluation will probably determine the future of LORAC in Monterey Bay. But if it is to continue and expand in use, the next logical step is to convert it to a system giving accurate geographical position. This will require relocating the antennas of Moss Landing and Santa Cruz to sites free from metal objects, and movement of the loop antennas to points at least 500 feet from the transmitting antennas. The antenna locations must be determined to within a foot with respect to each other. At that time it would probably be more convenient to switch from the Universal Transverse Mercator Projection to the California rectangular grid (based on yards), since many bench marks are already given in that system. This would make it easier to establish calibrating points at

at various locations, but a means for converting from the California system to geographical coordinates would have to be found. The transformation from UTM to geographic coordinates is described in the Computer's Manual. Special areas, such as that off Cannery Row, would require study to determine their effect on the hyperbolic position lines. The project is an ambitious one, but entirely within the realm of feasibility.

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APPENDIX

LORAC GRID CHART PLOTTING PROGRAM

```
//SHR20106   JOB   (0106,13FP),'....SHRUM....',MSGLEVEL=1
//  EXEC FORTCLG,REGION.GO=100K,TIME.GO=6
//FORT.SYSIN DD *
      IMPLICIT REAL*8(O-Z)
      REAL X, Y, LABEL/4H    /,SCALE
      REAL*8 LABEL1/8H GRN RED/,ITITLE(12)/'..SHRUM..GRID        OF LORA
     1C NAVIGATION SYSTEM (DISTANCES IN METERS).
     2  '/,LABEL2/8H        /
      DIMENSION ZF(2),ZCL(2),ZH(2),ZK(2),ZC2(2),ZCOSA(2),ZSINA(2),
     1 ZW(2),ZTOTL(2),X(900),Y(900),CX(30),CY(30),DX(18),DY(18)
C  ENTER MOST UP-TO-DATE INFORMATION ON RECTANGULAR COORDINATES OF ANTENNAS,
C  OPERATING FREQUENCIES, AND VELOCITY OF PROPAGATION.
      READ(5,101)ZEM,ZNM,ZEG,ZNG,ZER,ZNR,ZF(1),ZF(2),ZFNG,ZFNR,
     1 ZFGM,ZFRM,VELPRG
C  ARBITRARILY ASSIGN A VALUE TO THE CENTER LANES. SUBSCRIPT 1 REFERS TO THE
C  GREEN PART OF THE NETWORK, AND SUBSCRIPT 2 THE RED PART.
      ZCL(1)=1000.0
      ZCL(2)=2000.0
C  CALCULATE THE NETWORK CONSTANTS. REFER TO FIGURE 5-6, COMPUTER'S MANUAL.
      ZH(1)=0.5*(ZEG+ZEM)
      ZK(1)=0.5*(ZNG+ZNM)
      ZH(2)=0.5*(ZER+ZEM)
      ZK(2)=0.5*(ZNR+ZNM)
      ZEGM=ZEG-ZEM
      ZERM=ZER-ZEM
      ZNGM=ZNG-ZNM
      ZNRM=ZNR-ZNM
      ZDG2=ZEGM**2+ZNGM**2
      ZDR2=ZERM**2+ZNRM**2
      ZDG=DSQRT(ZDG2)
      ZDR=DSQRT(ZDR2)
      ZC2(1)=ZDG2/4.0
      ZC2(2)=ZDR2/4.0
      ZCG=DSQRT(ZC2(1))
      ZCR=DSQRT(ZC2(2))
      ZCOSA(1)=ZEGM/ZDG
      ZCOSA(2)=ZERM/ZDR
      ZSINA(1)=ZNGM/ZDG
      ZSINA(2)=ZNRM/ZDR
      ZW(1)=VELPRG/(2.0*ZF(1))
      ZW(2)=VELPRG/(2.0*ZF(2))
      ZTOTL(1)=ZDG/ZW(1)
```

```
      ZTOTL(2)=ZDR/ZW(2)
      ZLCTRG=ZCL(1)-ZTOTL(1)/2.0
      ZLCTRR=ZCL(2)-ZTOTL(2)/2.0
      ZLENDG=ZCL(1)+ZTOTL(1)/2.0
      ZLENDR=ZCL(2)+ZTOTL(2)/2.0
      WRITE(6,333)
      WRITE(6,102)ZEM,ZNM,ZEG,ZNG,ZER,ZNR,ZF(1),ZF(2),ZFNG,ZFNR,
     1 ZFGM,ZFRM,VELPRG
      WRITE(6,303)
      WRITE(6,103)ZH(1),ZH(2),ZK(1),ZK(2),ZEGM,ZERM,ZNGM,ZNRM,ZDG2,ZDR2,
     1 ZDG,ZDR,ZC2(1),ZC2(2),ZCG,ZCR,ZCOSA(1),ZCOSA(2),ZSINA(1),ZSINA(2)
     2,ZW(1),ZW(2),ZTOTL(1),ZTOTL(2),ZLCTRG,ZLCTRR,ZCL(1),ZCL(2),
     3 ZLENDG,ZLENDR
   ENTER VALUES FOR PLOTTING GEOGRAPHIC POINTS OF INTEREST, AS FOLLOWS: (1)
   REFERENCE VALUES, (2) COASTLINE PLOT, AND (3) NAVIGATIONAL AIDS PLOT.
      READ(5,101)ZERY,ZNRY,ZEGY,ZNGY
      READ(5,101)(CX(I),CY(I),I=1,30)
      READ(5,101)(DX(I),DY(I),I=1,18)
C
C
   ENTER PARAMETERS OF DESIRED CHARTS, ANY NUMBER OF GRID CHARTS MAY BE PRO-
   DUCED, WITH ONE DATA CARD PER CHART.
  900 READ(5,210,END=800)XMIN,XMAX,YMIN,YMAX,DELLAN,DELMU,PMUMAX
      WRITE(6,333)
      WRITE(6,210)XMIN,XMAX,YMIN,YMAX,DELLAN,DELMU,PMUMAX
   PMUMAX SETS OUTER LIMIT ON HYPERBOLIC LINES, AND THE STANDARD VALUE OF 2.0
   MUST BE INCREASED FOR AREAS FAR FROM THE BASELINES.
      IF(PMUMAX.NE.0.0)GO TO 301
      PMUMAX=2.0
   DETERMINE NUMBER OF POINTS PER HYPERBOLIC LINE.
  301 ICALC=PMUMAX/DELMU+1.001
      ICALM1=ICALC-1
   COMPUTE CHART SCALE.
      SCALE=(XMAX-XMIN)/9.0
      PX=XMIN
      PY=YMIN
C
C
   PLOT LOCATION OF STATIONS, AND SET GRAPH SPECIFICATIONS.
      X(1)=ZEG-PX
      X(2)=ZEM-PX
      X(3)=ZER-PX
      Y(1)=ZNG-PY
      Y(2)=ZNM-PY
      Y(3)=ZNR-PY
      CALL DRAW(3,X,Y,1,4,LABEL1,ITITLE,SCALE,SCALE,0,0,2,2,9,15,1,L)
C
C
```

```
   PLOT POINTS FOR DRAWING IN THE APPROXIMATE COASTLINE.
      CFAC=1.0/1.093613
      DO 201 I=1,17
      CXM=ZER+(CX(I)-ZERY)*CFAC
      CYM=ZNR+(CY(I)-ZNRY)*CFAC
      X(I)=CXM-PX
      Y(I)=CYM-PY
  201 CONTINUE
      DO 202 I=18,30
      CXM=ZEG+(CX(I)-ZEGY)*CFAC
      CYM=ZNG+(CY(I)-ZNGY)*CFAC
      X(I)=CXM-PX
      Y(I)=CYM-PY
  202 CONTINUE
      CALL DRAW(30,X,Y,2,1,LABEL,ITITLE,SCALE,SCALE,0,0,2,2,8,8,1,L)
C
C
   PLOT POINTS SHOWING POSITION OF VARIOUS NAVAIDS.
      DO 251 I=1,14
      CXM=ZER+(DX(I)-ZERY)*CFAC
      CYM=ZNR+(DY(I)-ZNRY)*CFAC
      X(I)=CXM-PX
      Y(I)=CYM-PY
  251 CONTINUE
      DO 252 I=15,18
      CXM=ZEG+(DX(I)-ZEGY)*CFAC
      CYM=ZNG+(DY(I)-ZNGY)*CFAC
      X(I)=CXM-PX
      Y(I)=CYM-PY
  252 CONTINUE
      CALL DRAW(18,X,Y,2,2,LABEL,ITITLE,SCALE,SCALE,0,0,2,2,8,8,1,L)
C
C
   CALCULATE THE RECTANGULAR COORDINATES FOR PLOTTING HYPERBOLIC LINES. GREEN
   LANES COMPUTED FIRST, THEN RED.
      DO 401 IK=1,2
      NCALC=ZTOTL(IK)/(2*DELLAN)+1
      NCALM1=NCALC-1
      WRITE(6,303)
C
   CALCULATE POINTS FOR THAT HALF OF NETWORK NEAR CENTER STATION, ENDING WITH
   THE CENTER LANE.
      DO 501 ILAN=1,NCALC
   DETERMINE THE LANE NUMBER OF THE FIRST LINE TO BE CONSIDERED.
      PL=ZCL(IK)-(NCALC-ILAN)*DELLAN
      PA=(ZCL(IK)-PL)*ZW(IK)
      FB=DSQRT(ZC2(IK)-PA*PA)
      IP=1
```

```
      POINTS IN QUADRANT 2, STARTING AT OUTERMOST POINT.
         DO 701 IMU=1,ICALC
         PMU=PMUMAX-(IMU-1)*DELMU
         PE1=PA*ZCOSA(IK)*DCOSH(PMU)
         PE2=PB*ZSINA(IK)*DSINH(PMU)
         PN1=PA*ZSINA(IK)*DCOSH(PMU)
         PN2=PB*ZCOSA(IK)*DSINH(PMU)
         XX=ZH(IK)-PE1-PE2
         YY=ZK(IK)-PN1+PN2
      IF THE CALCULATED POINT FALLS WITHIN THE DESIRED AREA, STORE ITS COORDINATES
      IN A MATRIX FOR PLOTTING LATER.
         IF(.NOT.((XMIN.LE.XX.AND.XX.LE.XMAX).AND.
     1      (YMIN.LE.YY.AND.YY.LE.YMAX))GO TO 701
  711 X(IP)=XX-PX
      Y(IP)=YY-PY
      COUNT NUMBER OF POINTS STORED.
         IP=IP+1
         IPM1=IP-1
  701 CONTINUE
      POINTS IN QUADRANT 3, ENDING WITH OUTERMOST POINT.
         DO 702 IMU=1,ICALM1
         PMU=PMUMAX-(ICALM1-IMU)*DELMU
         PE1=PA*ZCOSA(IK)*DCOSH(PMU)
         PE2=PB*ZSINA(IK)*DSINH(PMU)
         PN1=PA*ZSINA(IK)*DCOSH(PMU)
         PN2=PB*ZCOSA(IK)*DSINH(PMU)
         XX=ZH(IK)-PE1+PE2
         YY=ZK(IK)-PN1-PN2
         IF(.NOT.((XMIN.LE.XX.AND.XX.LE.XMAX).AND.
     1      (YMIN.LE.YY.AND.YY.LE.YMAX))GO TO 702
  712 X(IP)=XX-PX
      Y(IP)=YY-PY
      IP=IP+1
      IPM1=IP-1
  702 CONTINUE
      IF 4 OR MORE POINTS FALL WITHIN LIMITS, PROCEED WITH PLOT.
         IF(IP.LT.5)GO TO 501
         LABEL=PL
         CALL DRAW(IPM1,X,Y,2,0,LABEL,ITITLE,SCALE,SCALE,0,0,2,2,8,8,1,L)
         WRITE(6,101)LABEL
  501 CONTINUE
C
C
      CALCULATE POINTS FOR HALF OF NETWORK NEAR END STATION, STARTING WITH THE
      LANE NEXT TO THE CENTER LANE.
         DO 502 ILAN=1,NCALM1
         PL=ZCL(IK)+ILAN*DELLAN
         PA=(PL-ZCL(IK))*ZW(IK)
```

```
      PB=DSQRT(ZC2(IK)-PA*PA)
      IP=1
C POINTS IN QUADRANT 1, STARTING AT OUTERMOST POINT.
      DO 703 IMU=1,ICALC
      PMU=PMUMAX-(IMU-1)*DELMU
      PE1=PA*ZCOSA(IK)*DCOSH(PMU)
      PE2=PB*ZSINA(IK)*DSINH(PMU)
      PN1=PA*ZSINA(IK)*DCOSH(PMU)
      PN2=PB*ZCOSA(IK)*DSINH(PMU)
      XX=ZH(IK)+PE1-PE2
      YY=ZK(IK)+PN1+PN2
      IF(.NOT.((XMIN.LE.XX.AND.XX.LE.XMAX).AND.
     1    (YMIN.LE.YY.AND.YY.LE.YMAX)))GO TO 703
  713 X(IP)=XX-PX
      Y(IP)=YY-PY
      IP=IP+1
      IPM1=IP-1
  703 CONTINUE
C POINTS IN QUADRANT 4, ENDING AT OUTERMOST POINT.
      DO 704 IMU=1,ICALM1
      PMU=PMUMAX-(ICALM1-IMU)*DELMU
      PE1=PA*ZCOSA(IK)*DCOSH(PMU)
      PE2=PB*ZSINA(IK)*DSINH(PMU)
      PN1=PA*ZSINA(IK)*DCOSH(PMU)
      PN2=PB*ZCOSA(IK)*DSINH(PMU)
      XX=ZH(IK)+PE1+PE2
      YY=ZK(IK)+PN1-PN2
      IF(.NOT.((XMIN.LE.XX.AND.XX.LE.XMAX).AND.
     1    (YMIN.LE.YY.AND.YY.LE.YMAX)))GO TO 704
  714 X(IP)=XX-PX
      Y(IP)=YY-PY
      IP=IP+1
      IPM1=IP-1
  704 CONTINUE
C IF 4 OR MORE POINTS FALL WITHIN LIMITS, PROCEED WITH PLOT.
      IF(IP.LT.5)GO TO 502
      LABEL=PL
      CALL DRAW(IPM1,X,Y,2,0,LABEL,ITITLE,SCALE,SCALE,0,0,2,2,8,8,1,L)
      WRITE(6,101)LABEL
  502 CONTINUE
  401 CONTINUE
C
C
C RE-PLOT THE LOCATION OF THE STATIONS, AND END THE GRAPH.
      X(1)=ZEG-PX
      X(2)=ZEM-PX
      X(3)=ZER-PX
      Y(1)=ZNG-PY
```

```
      Y(2)=ZNM-PY
      Y(3)=ZNR-PY
      CALL DRAW(3,X,Y,3,2,LABEL2,ITITLE,SCALE,SCALE,0,0,2,2,8,8,1,L)
C
C
   RETURN TO DATA DECK TO CHECK FOR MORE CHARTS.
      GO TO 900
  800 STOP
  101 FORMAT(2F20.3)
  102 FORMAT(/ 5X,2F25.3)
  103 FORMAT(// 10X,2F25.8)
  104 FORMAT(20X,2F20.5)
  210 FORMAT(6F12.3,F8.3)
  303 FORMAT(1H0)
  333 FORMAT(1H1)
      END
```

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13. ABSTRACT

A navigation system has been established on Monterey Bay using the LORAC principle of phase-comparison. It is intended primarily for use in ocean sciences research within a 25 mile radius of Moss Landing, California. The system offers the capability of repeating a previously held position within a few feet, and may be used as a general navigation aid in the area with accuracy on the order of 100 yards. The theory of operation and error-causing factors are discussed in detail. Transmitter and receiver installations are described. Chapter IV is intended to serve as a self-contained user's guide, with instructions on the operation of the receiver, suggested techniques for use, and a description of the performance to be expected. A computer program is included to provide grid charts with hyperbolic position lines plotted for any desired area or scale. Brief initial testing indicated a high degree of stability and repeatability, however further evaluation over a longer period is necessary.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
NAVIGATION SYSTEM						
LORAC						
POSITION FIXING						
HYPERBOLIC NAVIGATION SYSTEM						

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